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16. ABSTRACT

EPA's Office of Research and Development initiated the Environmental Monitoring and Assessment Program (EMAP) to provide data for better assessments of the condition of the nation's ecological resources. Over the next five years, several integrated monitoring networks will be implemented to (1) estimate current status, extent, changes, and trends in indicators of ecological condition, (2) monitor indicators of pollutant exposure and habitat condition and seek associations among indicators that provide plausible explanations for adverse condition; and (3) provide periodic reports on status and trends to the EPA Administrator and the public. These networks will yield statistically unbiased estimates with quantifiable confidence limits on regional and national scales for periods of years to decades. This report presents the approach proposed to describe ecological condition; defines a common strategy within the program for selecting, prioritizing, and evaluating indicators; and serves as a means to seek expert advice and relevant data from the scientific community that might aid the refinement and execution of the indicator strategy. The report also summarizes the indicators chosen for evaluation as core indicators, which will be implemented in regional and national monitoring of six categories of resources: near-coastal waters, inland surface waters, wetlands, forests, arid lands, and agroecosystems.

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EXECUTIVE SUMMARY

In 1988 the Science Advisory Board of the U.S. Environmental Protection Agency (EPA) recommended implementing a program within EPA to monitor the status and trends of ecological condition and to develop innovative methods for anticipating emerging problems before they become crises. More recently, EPA established a program aimed at *monitoring for results*; that is, confirming that the nation's environmental protection efforts are truly maintaining or improving environmental quality. EPA's Office of Research and Development (ORD) began planning the Environmental Monitoring and Assessment Program (EMAP) in response to these needs for better assessments of the condition of the nation's ecological resources. Planning is being conducted in cooperation with other agencies and organizations that share responsibilities for renewable natural resources or environmental quality.

When fully implemented, EMAP will answer several critical questions: What is the current extent of our ecological resources, and how are they distributed geographically? What proportions of the resources are currently in good or acceptable condition? What proportions are degrading or improving, in what regions, and at what rate? Are these changes correlated with patterns and trends in environmental stresses? Are adversely affected resources improving overall in response to control and mitigation programs?

EMAP scientists will answer these questions by designing and implementing over the next five years integrated monitoring networks with the following objectives.

- Estimate current status, extent, changes, and trends in indicators of the condition of the nation's ecological resources on a regional basis with known confidence
- Monitor indicators of pollutant exposure and habitat condition and seek associations between human-induced stresses and ecological condition
- Provide periodic statistical summaries and interpretive reports on status and trends to the EPA Administrator and the public

EMAP networks will provide statistically unbiased estimates of status, trends, and associations with quantifiable confidence limits over regional and national scales for periods of years to decades. EMAP will also provide a framework for cooperative planning and implementation with other agencies and organizations that have active monitoring programs in the ecological and natural resource areas. This framework will provide for direct integration of these data, where appropriate, and will enable EMAP to supplement existing networks to fill data gaps, if necessary.

PURPOSE OF THIS DOCUMENT

The purpose of this document is threefold: (1) to inform potential EMAP data users of the approach proposed to describe ecological condition; (2) to define a strategy for evaluating, prioritizing, and selecting indicators that will facilitate coordination and integration among each of six EMAP resource categories; and (3) to seek expert advice and environmental data sets from the scientific community that are needed to better characterize the spatial and temporal variability of the proposed indicators on a regional scale.

EMAP BACKGROUND

Six broad **ecological resource categories** have been defined within EMAP: near-coastal waters, inland surface waters, wetlands, forests, arid lands, and agroecosystems. Within each of these categories, several

ecological resource classes have been identified (e.g., large estuaries, small lakes, emergent estuarine wetlands, oak-hickory forests, sagebrush-dominated shrubland, and orchard cropland). In addition to measures of extent (numbers, length, area), EMAP will make routine measurements of environmental indicators on **resource sampling units** selected from each of these resource classes. The measurements will be used to provide regional- and national-scale assessments of the condition of the nation's resources.

The EMAP sampling design will lead to unbiased estimates with known confidence of the extent of resource classes and their current ecological condition. The design must also be sufficiently flexible to accommodate sampling of many distinct resource classes and identification of emerging environmental issues, as well as to associate resource condition with pollutant exposure, habitat condition, and natural and human-induced stresses.

The proposed sampling design uses a systematic triangular sampling grid of points randomly placed over the United States. Grid density can be increased or decreased to meet specific needs, but the baseline density is approximately one point per 640 km^2, which results in about 12,600 points across the contiguous United States and approximately 2,400 and 56 points in Alaska and Hawaii, respectively. Next, a two-stage process is used to select points from the grid for landscape description and sampling site selection. In the first stage, a set of points is selected by using probability methods; the landscape within a hexagonal area (**landscape sampling unit**) centered on each of these grid points then will be characterized (by using maps, aerial photography, and satellite imagery) to estimate the extent of each resource class and to facilitate selection of resource sampling units upon which indicators will be measured. In the second stage of the process, a subset of resource sampling units is selected for each resource class from which regional population estimates are to be made. Because the points represent a probability sample, the measurements of resource extent and environmental indicators can be extrapolated to yield estimates for resource classes for regions or the entire nation.

Placement of the grid determines the ultimate sampling location, and many of the sampling sites will not be available for intensive or continuous monitoring. Also, indicators must be measured on an adequate number of resource sampling units to make regional population estimates with sufficiently narrow confidence bounds. EMAP will therefore operate as a series of annual surveys, measuring indicators during a particular season or other time period that is likely to be specific to each resource category and possibly to each resource class. For example, late summer may be selected as the **index period** for making measurements on fish populations, when stream flows and dissolved oxygen levels may be lowest and effects of stressors may be highest.

EMAP's objectives include describing current condition as well as documenting trends in condition. Optimal achievement of either objective would require different designs; the EMAP design resolves this issue by selecting distinct subsets of resource sampling units each year in a four-year cycle, returning to the first year's subset in the fifth year; a particular site therefore will be sampled only every fourth year, and condition estimates will be based on four-year running averages. Regional or national trends are expected to be discernible within 10-15 years. Because individual sites are sampled only once every four years, and 10-15 site visits are required to detect a trend, EMAP will provide little information about the conditions at any *particular site* for a period of 40-60 years. This probability-based survey approach places important constraints on indicator selection.

INDICATOR STRATEGY

In EMAP, we have defined several categories of indicators - response, exposure, habitat, and stressor, examples of which are given in Figure 1. **Response indicators** are characteristics of the environment measured to provide evidence of the biological condition of a resource at the organism, population, community, or ecosystem level of organization. **Exposure** and **habitat indicators** are diagnostic indicators that are measured in conjunction with response indicators. Exposure indicators are characteristics of the environment measured to provide evidence of the occurrence or magnitude of a response indicator's contact with a physical, chemical, or biological stress. Habitat indicators are physical attributes measured to characterize conditions necessary to support an organism, population, or community in the absence of pollutants. **Stressor indicators** are characteristics measured to quantify a natural process, environmental hazard indicators, or a management activity that effect changes in exposure and habitat. Response, exposure, and habitat indicators will be measured during annual surveys at sampling sites associated with points on the EMAP grid. Stressor indicators normally will not be measured at the sampling sites; instead, stressor data will usually be obtained from other monitoring programs.

EMAP will use response indicators to describe ecological condition. Exposure and habitat indicators will be used to provide plausible explanations for observed differences and changes in response indicators, and stressor indicators will be used to identify possible causes for changes in exposure and habitat indicators. Analyses will rely on correlative empirical approaches and thus cannot prove causality. The use of correlative approaches will, however, identify hazards that are geographically widespread, most intense, or associated

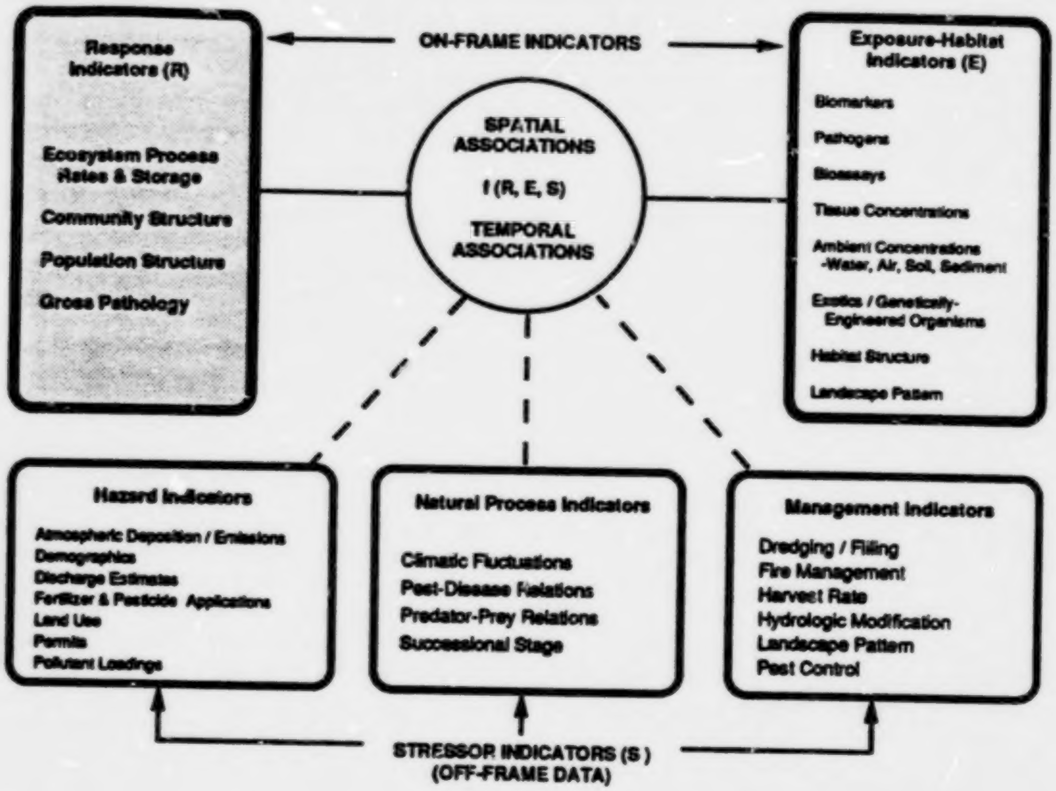

Figure 1. **EMAP conceptual indicator strategy. Indicators are objective, quantifiable surrogates for assessment endpoints and stressors (environmental hazards, management actions, and natural phenomena). The circle indicates that analysis is by statistical association, rather than by explicit (causal) mathematical relationships.**

with most rapid deterioration. Once EMAP indentifies a geographic area with a high proportion of a resource in unacceptable condition, other projects must be designed and implemented to pinpoint causes and solutions.

EMAP also must present its results in such a way that they are readily interpretable by the public and by decision-makers. Assigning a threshold value to response indicators that will enable decision-makers and the public to distinguish "good" ecological condition from "bad" ecological condition is not possible a *priori*, because public perceptions of ecological "health" can differ from region to region and can change with time. Also, ecological condition may reflect exposure to a multitude of environmental stresses including those that are related to human activities and those that are natural. Which indicators to implement in a long-term monitoring program that will provide the most cost-effective information on the status and trends of ecological condition must be carefully evaluated, and the effective use of relevant data collected by other operational monitoring programs clearly requires careful consideration.

Several other issues related to interpretation and summary presentations of indicator data require resolution. These include addressing situations when resource sampling units in poor condition are associated with multiple exposure or habitat indicators. The use of indices, which are mathematical combinations of indicator values, provides a means to rank resources on an acceptable-to-unacceptable continuum based on multiple measurements. Research is needed to select the most appropriate mathematical schemes to combine data that will summarize results without losing critical information.

Geographic information systems provide the opportunity to overlay patterns in exposure, habitat, or stressor indicators onto patterns in response indicators across broad geographic regions to provide plausible explanations why ecological condition in some regions is unacceptable (or appears to be degrading) or acceptable (or appears to be improving). EMAP also will investigate the use of multivariate statistical techniques in analyzing regional data sets. Finally, retrospective analysis techniques will be investigated for EMAP as a possible means of evaluating current ecological condition at single sites and over larger areas, where archived remote sensing or other data are available.

INDICATOR SELECTION

To compile the sets of research indicators presented in this document, each Resource Group began evaluating **candidate indicators** (Figure 2) that had been proposed for their resource categories over the past three decades. Draft criteria for research indicator selection were formulated, and a final matrix was developed. Each group judged its candidate indicators against this matrix to identify a set of **research indicators** believed to be most promising for further evaluation. Comments on this document from 22 external peer reviewers and the EPA Science Advisory Board were used to refine these indicator sets and the EMAP indicator strategy. High-priority research indicators must have well-established, readily standardized methods and a reasonable amount of available environmental data; they must pass a second round of testing (existing data analysis, simulation, and local field tests) before being considered **developmental indicators** that are suitable for regional demonstration projects. Those developmental indicators that are selected for long-term implementation are termed **core indicators** (Figure 2).

The application of the EMAP indicator strategy to develop a list of research indicators is described separately for each resource category. Each description begins with a discussion of past and current monitoring efforts and a premliminary list of EMAP resource classes specific to the category. Introductory comments are followed by a description of the indicator selection process, including public perceptions of the resource category, environmental hazards affecting the resource, research indicators appropriate for EMAP, and candidate indicators not appropriate for EMAP. Next is a discussion of how the research indicators would be applied as a comprehensive set to assess ecological condition and how that condition would be correlated

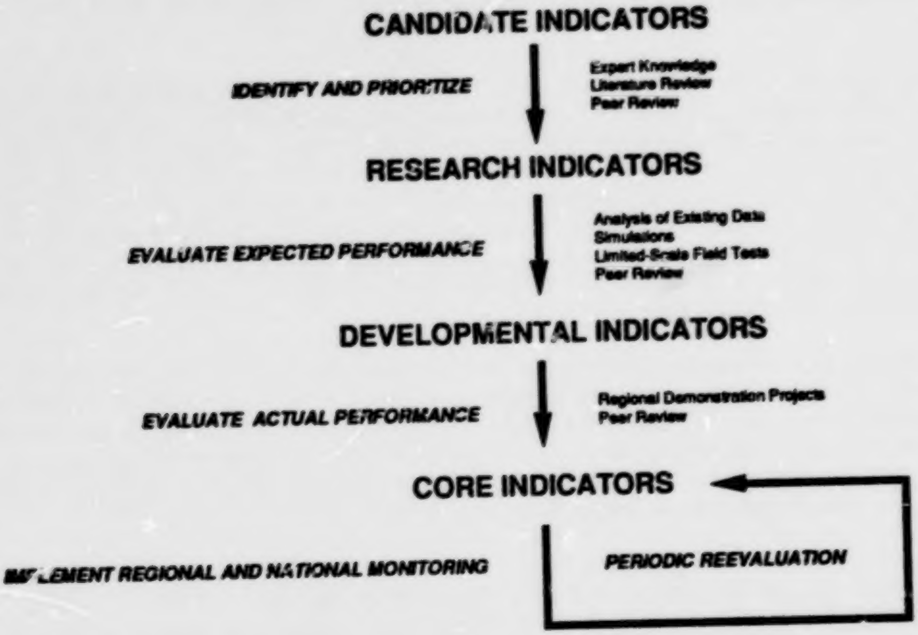

Figure 2. Indicator selection, prioritization, and evaluation approach for EMAP.

with patterns and trends in environmental stresses. Each discussion concludes with a summary of research needs that are crucial for conducting regional survey monitoring in the respective resource categories.

Another set of indicators that are likely appropriate for determining condition in several ecological resources was compiled by scientists with expertise in animal ecology, biomarkers, and landscape ecology. These indicators will be included as part of the indicator sets, as appropriate, for each ecological resource when routine, operational monitoring is implemented.

Finally, indicators of atmospheric stressors were also evaluated. Atmospheric deposition and gaseous compounds typically require continuous monitoring, at least over some index periods, to produce data that are useful for a long-term monitoring program. Access to randomly chosen sites, the large numbers of EMAP sites, and the start-up costs of a new network prohibit EMAP from being capable of routinely monitoring atmospheric stressors as part of the EMAP grid. Therefore, it is suggested that the most efficient way for EMAP to acquire data on atmospheric stressor indicators is by using existing networks within the context of the EMAP probability-based sampling design. Regional estimates of deposition and exposure could be obtained by fitting surfaces to the atmospheric monitoring data.

The document concludes by presenting an indicator matrix (Table 1) that lists all EMAP research indicators by indicator type and resource category. The matrix includes those indicators that are undergoing further evaluation as well as those that the resource groups chose not to evaluate further at this time.

FUTURE RESEARCH

The next step in the EMAP indicator development strategy is twofold: (1) evaluation of the potential effectiveness of each research indicator for use in quantitative regional assessments of ecological condition by analyzing existing regional data sets and (2) evaluation of additional candidate indicators in order to fill gaps in the indicator strategy for each resource category. Unfortunately (as is evident in the indicator fact sheets), few regional data sets exist that are derived from probability sampling. Therefore, we currently are unable to determine the effectiveness of indicator measurements for long-term, regional monitoring. If such data sets are inadequate or nonexistent, local field tests will be used to obtain the statistical parameters necessary to evaluate each research indicator.

This document serves as the initial basis for the development of an indicator research plan to be implemented for long-term monitoring in EMAP. The concepts presented here are intended to facilitate consistency among the resource groups in selecting, evaluating, and developing indicators for monitoring. Over the long term, EMAP also will undertake a research program on indicators. An international workshop will be held in October 1990 to begin this process. Long-term research will focus, in part, on fundamental understanding of what constitutes desirable ecological condition and what factors are indicative of stability and resilience that confer long-term sustainability.

ACRONYMS

AFA - American Forestery Association

ANC - acid-neutralizing capacity

ARNEWS - Acid Rain National Early Warning System

ASTM - American Society for Testing and Materials

AVHRR - Advanced Very High Resolution Radiometer

BBS - Breeding Bird Survey

BCI - Biotic Condition Index

BLM - Bureau of Land Management

BOD - biochemical oxygen demand

CBC - Christmas Bird Count

CHC - chlorinated hydrocarbon

CPUE - cost per unit effort

CV - coefficient of variation

DBH - diameter at breast height

DIC - dissolved inorganic carbon

DO - dissolved oxygen

DOC - dissolved organic carbon

ELISA - enzyme-linked immunosorbent assays

EMAP - Environmental Monitoring and Assessment Program

EPA - U.S. Environmental Protection Agency

FDA - Food and Drug Administration

FIA - Forest Inventory and Analysis (USDA-FS program)

FIFRA - Federal Insecticide, Fungicide and Rodenticide Act

FLPMA - Federal Lands Policy and Management Act

FPM-MAG - Forest Pest Management, Methods Application Group (USFS)

FWS - Fish and Wildlife Service

GAO - General Accounting Office

GC - gas chromatography

GEM - global environmental monitoring

GIS - Geographic Information System

HCN - Historic Climatic Network

HLI - Habitat Layers Index

HLCS - Habitat Linear Classification System

HQA - habitat quality index

IBI - index of biotic integrity

ICP - inductively coupled plasma

LAI - leaf area index

LDI - Landscape Development Intensity (index)

LHQI - Lake Habitat Quality Index

LTER - long-term ecological research

MCI - macroinvertebrate community index

MIS - management indicator species

MPDI - Microwave polarization difference index

MS - mass spectrometry

MSS - multispectral scanner

NADP - National Acid Deposition Program

NAPAP - National Acid Precipitation Assessment Program

NAS - National Academy of Scienc

NASA - National Aeronautics and Space Administration

NASQAN - National Stream Quality Accounting Network

NBS - National Bioaccumulation Study

NDDN - National Dry Deposition Network

NDVI - normalized difference vegetation index

NEPA - National Environmental Policy Act

NOAA - National Oceanic and Atmospheric Administration

NPDES - National Pollution Discharge Elimination System

NPP - net primary productivity

NPS - National Park Service

NRC - National Research Council

NS&T - National Status and Trends (program of NOAA)

NSWS - National Surface Water Survey

NTN - National Trends Network

NWI - National Wetland Inventory

ORD - Office of Research and Development

PAH - polycyclic aromatic hydrocarbon

PCB - polychlorinated biphenyl

pH - inverse log concentration of H^+ ion

RCRA - Resource Conservation and Recovery Act

RPA - Renewable Resources Planning Act

SAV - submerged aquatic vegetation

SHQI - Stream Habitat Quality Index

TDS - total dissolved solids

TKN - total Kjeldahl nitrogen

TM - Thematic Mapping

TOC - total organic carbon

TSI - trophic state index

TSS - total suspended solids

UNEP - United Nations Environment Programme

USDA - U.S. Department of Agriculture

USDA-FS - U.S. Department of Agriculture, Forest Service

USDOI - U.S. Department of the Interior

GLOSSARY[3]

Assessment endpoint - A quantitative or quantifiable expression of the environmental value being considered in the environmental analysis; examples include a 25% reduction in gamefish biomass or local extinction of an avian species (Suter 1990).

Best management practices - Management practices targeted at minimizing specific watershed disturbances, such as soil erosion, pollutant transport, stormwater runoff, or similar land-use-related disturbances.

Biodiversity - A conceptual term referring to the variety and variability among living organisms and the ecological complexes in which they occur; diversity can be defined as the number of different items and their relative frequencies. For biological diversity, these items are organized at many levels, ranging from complete ecosystems to the chemical structures that are the molecular basis of heredity. Thus, the term encompasses different ecosystems, species, genes, and their relative abundance (OTA 1987).

Biomarker - An indicator of cellular or physiological processes that signal events in biological systems or samples. A biological marker of effect may be an indicator of an endogenous component of the biological system, a measure of the functional capacity of the system, or an altered state of the system that is recognized as impairment or disease. A biological marker of exposure may be the identification of an exogenous substance within the system, the interactive product between a xenobiotic compound and endogenous components, or other event in the biological system related to the exposure (NRC 1987).

Bottom-up approach - Assessing ecological condition based on first principles, i.e., pollutant effects are related causally to pollutant sources by transport and fate models.

Candidate indicator - Indicator identified for each resource category by using a combination of literature review, expert workshops, and interviews with scientists and environmental managers, which was then judged against specific EMAP criteria to determine its feasibility as a research indicator.

Characterization - The documentation of essential traits.

Classification - A hierarchical partitioning of ecological resource categories based on increasing similarity of specifically defined attributes (e.g., lakes classes can be distinguished by size - large lakes versus small lakes; the small lake class can be further partitioned by hydrologic lake type - small seepage lakes versus small drainage lakes); a procedure by which land areas are identified and assigned to particular categories, on the basis of specific guidelines related to observed characteristics or attributes.

Core indicator - EMAP indicator that is selected for long-term, routine monitoring based on its performance as demonstrated in a regional demonstration project.

Cumulative frequency distribution - A distribution generated by a function ($F(x)$) such that at any value for the variable x, $F(x)$ represents the proportion of the resource sampling units in the target population having a value for the variable that is less than or equal to x. In EMAP, x is usually a measurement of physical extent or an indicator measurement.

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[3] The definitions of these terms are operational at the time of this writing; some terms may be used within EMAP in slightly different ways depending on the specific resource category to which they are applied. It is anticipated that the definitions for some terms will be refined as EMAP progresses.

Developmental indicator - An EMAP indicator that has passed evaluation for expected performance (existing data analyses, simulation, and small-scale field tests) and, with the concurrence of scientific peer reviewers, is deemed suitable for actual performance testing in a regional demonstration project.

Diagnostic indicator - Characteristics of the environment measured for the purpose of correlative analysis to determine plausible explanations for subnominal conditions; a collective term for EMAP exposure, habitat, and stressor indicators.

Ecological indicator - Response indicator.

Ecological resource category (resource category) - The aggregations of ecological resource classes that are conveniently dealt with by ecologists with specific disciplinary expertise; six categories currently are identified: near-coastal waters, inland surface waters, wetlands, forests, arid lands, and agroecosystems. ecosystems.

Ecological resource class (resource class) - A subdivision of an ecological resource category; examples include small lakes, oak-hickory forests, emergent estuarine wetlands, field cropland, mesohaline estuaries, and sagebrush dominated desert scrub.

Ecological risk assessment - The application of a formal framework to estimate the effects of human action on a natural resource and to interpret the significance of those effects in light of the uncertainties identified in each component of the assessment process. Steps in the framework include initial hazard identification, exposure assessment, dose-response assessment, and risk characterization.

Ecosystem - A local complex of interacting plants, animals, and their physical surroundings which is generally isolated from adjacent systems by some boundary, across which energy and matter move; examples include a watershed, an ecoregion, or a biome.

Ecosystem function - Attributes of the rate of change of structural components of an ecosystem; examples include primary productivity, denitrification rates, and species fecundity rates.

Ecosystem structure - Attributes of the instantaneous state of an ecosystem; examples include species population density, species richness or evenness, and standing crop biomass.

Environmental indicators - A collective term for response, exposure and habitat, and stressor indicators.

Explicit sampling frame - The representation of a target population (resource category, class, or subclass), each unit of which has a unique identification code, used to implement a sampling strategy; an example includes a list of all lakes greater than 4 ha in the Northeast.

Exposure indicator - A characteristic of the environment measured to provide evidence of the occurrence or magnitude of a response indicator's contact with a physical, chemical, or biological stress.

Habitat indicator - A physical attribute measured to characterize conditions necessary to support an organism, population, or community in the absence of pollutants.

Hazard - A state that may result in an undesired event; the cause of risk. In EMAP, any human-related event or activity that unintentionally or inadvertently can affect ecological condition; examples are acidic deposition that may decrease the acid-neutralizing capacity of surface water, or application of fertilizer to a forested watershed that may increase nutrient levels in adjacent streams.

Hazard indicator - Measures that reflect human activities that unintentionally affect ecological resources (e.g., measures of pollutant release, number of permits issued for construction activity, and rates of application of fertilizers to forests and crops that influence nutrient concentrations in adjacent streams).

Implicit sampling frame - A set of rules or criteria used to select resource sampling units that cannot be listed a *priori* by a unique identification code (upon which indicators will be measured); the rules are developed as part of the landscape characterization activities performed on the landscape sampling units.

Index (indices) - Mathematical aggregation(s) of indicators or metrics; one example is the Index of Biotic Integrity (IBI), which combines several metrics describing fish community structure, incidence of pathology, population sizes, and other characteristics.

Index period - Sampling period that yields the maximum amount of information during the year, which may vary from one indicator or resource class to another.

Indicator - A characteristic of the environment that, when measured, quantifies the magnitude of stress, habitat characteristics, degree of exposure to the stressor, or degree of ecological response to the exposure.

Interpenetrating design - The monitoring survey design used in EMAP, in which a new set of resource sampling units (RSUs) is selected each year during four successive years. The four-year cycle is repeated by using the same set of RSUs as in the first cycle; therefore, the same set of RSUs sampled in year 1 would be resampled in year 5.

Kriging - A weighted, moving-average estimation technique based on geostatistics that uses the spatial correlation of point measurements to estimate values at adjacent, unmeasured points.

Landscape - The fundamental traits of a specific geographic area, including its biological composition, physical environment, and anthropogenic or social patterns.

Landscape characterization - The documentation of principal components and patterns of landscape structure, including attributes of the physical environment, biological composition, and cultural patterns. In EMAP, a term referring to the process of describing land use or land cover within the landscape sampling units.

Landscape ecology - The study of the distribution patterns of communities and ecosystems, the ecological processes that affect those patterns, and changes in pattern and process over time (Forman and Godron 1986).

Landscape indicator - A characteristic of the environment, calculated from remotely sensed data, used to describe spatial distribution of physical, biological, and cultural features across a geographic area.

Landscape sampling unit - The selected units (e.g., 40-km^2 hexagons) upon which landscape characterization will be performed.

Management indicator - Measures that reflect human activities that intentionally alter an ecological resource to meet some management objective; for example, the dredging or filling of a wetland for the purpose of housing development.

Maximum/minimum operators approach - A mathematical aggregation scheme used to produce an ecological condition index based on several response indicator values; the index assumes the value of the most subnominal indicator.

Measurement endpoint - A quantitative summary of the results of a biological monitoring study, a toxicity test, or other activity intended to reveal the effects of a stressor or hazard.

Natural process indicator - Measures that reflect cyclic or acyclic phenomena that affect ecological condition, regardless of the presence of management actions or environmental hazards; examples include natural climatic fluctuations, predator-prey cycles, and insect and disease epidemics.

Nominal - The state of having desirable or acceptable ecological condition.

Population estimate - A statistical estimate of some characteristic (or distribution of characteristics) that applies to an explicitly defined target population (category, class, or subclass), e.g., the median acid-neutralizing capacity (or the cumulative frequency distribution of acid-neutralizing capacity) for all small lakes in the Northeast.

Probability sample/sampling - A sample chosen in such a manner that the probability of each selected unit is known; for EMAP, each resource sampling unit (e.g., a lake, a forest, an estuary) upon which indicator measurements are to be made will have a known probability of being selected.

Region - Any extensive geographic area that generally corresponds in size to EPA administrative Regions III through X (e.g., physiographic regions, ecoregions, major river basins).

Regional ecological resource class (regional resource class) - An ecological resource class that is distributed over some natural spatial range, e.g., southeastern oak-hickory forests or small lakes in the Northeast.

Regional reference site - One of a population of benchmark or control sites that, taken collectively, represent an ecoregion or other broad biogeographic area; the sites, as a whole, represent the best ecological conditions that can be reasonably attained, given the prevailing topography, soil, geology, potential vegetation, and general land use of the region.

Research indicator - A candidate indicator identified for an EMAP resource category which has been prioritized on the basis of several criteria (e.g., regionally applicable, integrates effects, monotonic, conducive to synoptic monitoring) and, following peer review, has been selected for further evaluation for use in EMAP, as possible developmental indicators; evaluation of expected performance includes analyzing existing data, performing simulation studies with realistic scenarios and expected spatial and temporal variability, and conducting limited field tests.

Resource sampling unit - A particular ecological resource (e.g., a stream segment, a forest stand, a wetland, an estuary) upon which indicator measurements will be made; more than one resource sampling unit can occur in a landscape sampling unit.

Response indicator - A characteristic of the environment measured to provide evidence of the biological condition of a resource at the organism, population, community, or ecosystem process level of organization.

Stressor indicator - A characteristic measured to quantify a natural process, an environmental hazard, or a management action that effects changes in exposure and habitat.

Stressor - Measurements used to provide information on human activities or externalities that can cause stress in ecological entities; three types of stressor indicators are considered in EMAP: hazard indicators, management indicators, and natural process indicators. Examples are the incidence of fertilizer application, which can increase nutrient concentrations in lakes; incidence of dredging/filling, which can diminish availability of wetland habitat; and climatic fluctuations, which can promote damage by pathogens.

Subnominal - The state of having undesirable or unacceptable ecological condition.

Target population - The set of ecological resources from which a sample is drawn.

Threshold - The value for a particular response indicator used to distinguish nominal from subnominal ecological condition.

Tier 1 resource sample - All resource sampling units of each resource class within all landscape sampling units.

Tier 2 resource sample - A subsample of the Tier 1 resource sample used for field sampling of indicators.

Top-down approach - Assessing ecological condition based on correlative analyses; i.e., pollutant effects are associated temporally or spatially with pollutant sources by statistically correlational analysis.

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SECTION 1

BACKGROUND

1.1 EMAP AND THE NEED FOR ECOLOGICAL MONITORING

Increasingly, reports appear on symptoms of current or potential ecological problems: declining fish and shellfish harvests and toxic algal blooms in near-coastal waters, dying high-elevation forests, diseased and cancerous fish in lakes and rivers, and decreasing biodiversity. We presently lack an integrated approach to monitoring indicators of ecological condition and indicators of pollutant exposure and habitat loss or degradation in our ecological resources. We therefore cannot determine whether the frequency and extent of the problems are increasing on a regional scale, whether such patterns are warning indicators of significant long-term changes in ecological condition, or whether such patterns are natural or are associated with changes in ambient pollutant levels or other human activities. The lack of a framework for efficiently using data collected by the U.S. Environmental Protection Agency (EPA) and other organizations or a monitoring scheme to fill the critical gaps in existing data means that ecological assessments of most new environmental issues take four to five years to produce useful results. The need to establish baseline conditions against which future changes can be documented with confidence has grown more acute with the increasing complexity, scale, and social importance of environmental issues such as acidic deposition, global atmospheric change, and declining biodiversity.

EPA, the U.S. Congress, and private organizations with environmental and natural resource interests have long recognized the need to fill this critical data gap. Congressional hearings in 1983 and 1984 on the National Environmental Monitoring Improvement Act led to the conclusion that despite hundreds of millions of dollars spent annually on environmental monitoring, federal agencies could assess neither the current status of ecological resources nor the overall progress toward legally mandated goals (U.S. House of Representatives 1984). More recently, Portney (1988) called for a Bureau of Environmental Statistics, and Roughgarden (1989) suggested a U.S. ecological survey to remedy these shortcomings. In 1988, the EPA Science Advisory Board recommended that a program be implemented within EPA to monitor ecological status and trends, as well as to develop innovative methods for anticipating emerging problems before they reach crisis proportions (U.S. EPA 1988). EPA's Office of Research and Development (ORD) began planning the Environmental Monitoring and Assessment Program (EMAP) in response to this strongly and widely felt need. EMAP is fully consistent with recent directives within EPA aimed at *managing for results*, that is, confirming that the nation's environmental protection efforts are truly maintaining or improving environmental quality.

The need for better environmental monitoring systems is not restricted to emerging problems. ORD provides much of the scientific basis for regulatory programs estimated to cost billions of dollars annually. The Conservation Foundation (1987) estimated 1985 annual expenditures at $65 billion in 1982 dollars, and the National Association of Manufacturing put the current estimate at $70 billion a year (ES&T 1989). The most common approach couples single-species laboratory tests; computer models that predict pollutant transport, fate, and exposure in the environment; and dose-response models that relate the resulting exposures to the corresponding effects on biota. Years of peer review have left little doubt that this approach forms a rational scientific basis for the regulation of *individual* pollutants. The potential for differential toxicity of pollutants to sensitive species, different life stages of the same species, ecological compensation and magnification, cumulative effects, and cascading effects on ecosystem trophic structure, however, all point to the need for validating our current approach through ongoing surveillance of indicators of ecological condition.

We are obviously not without environmental monitoring data. Approximately $350 million is spent each year within EPA on environmental monitoring, about half of which is associated with ambient monitoring.

This amount is at least equaled in relevant monitoring activities by other federal, state, and private organizations. Lack of comparability of data among programs, the absence of a framework within which to integrate data across networks, and failure to measure indicators that adequately reflect public concerns, however, have thus far prevented these efforts from meeting the critical needs for reliable national assessments of ecological condition.

1.2 THE ENVIRONMENTAL MONITORING AND ASSESSMENT PROGRAM

When fully implemented, EMAP will answer critical questions for policymakers, decision-makers, and the public: What is the current extent of our ecological resources, and how are they distributed geographically? What proportions of the resources are currently in good or acceptable condition? What proportions are degrading or improving, in what regions, and at what rate? Are these changes correlated with patterns and trends in environmental stresses? Are adversely affected resources improving overall in response to control and mitigation programs?

To answer these questions, EMAP scientists will design and implement a number of long-term, integrated monitoring networks over the next five years with the following objectives.

- Estimate current status, extent, changes, and trends in indicators of the condition of the nation's ecological resources on a regional basis with known confidence

- Monitor indicators of pollutant exposure and habitat condition and seek associations between human-induced stresses and ecological condition

- Provide periodic statistical summaries and interpretive reports on ecological status and trends to the EPA Administrator and the public

These EMAP networks will provide statistically unbiased estimates of status, trends, and relationships with quantifiable confidence limits over regional and national scales for periods of years to decades. EMAP will also provide a framework for cooperating with other agencies that have active monitoring programs that address some of EMAP's needs for certain resources. This framework will provide for direct integration of these data, where appropriate, and will enable EMAP to supplement the coverage of existing networks to fill critical data gaps, if necessary.

EMAP consists of five basic activities: (1) strategic evaluation, development, and testing of indicators of ecological condition, pollutant exposure, and habitat condition; (2) design and evaluation of integrated statistical monitoring frameworks and protocols for collecting data on indicators; (3) nationwide characterization of the extent and location of ecological resources; (4) demonstration studies and implementation of integrated sampling designs; and (5) development of data handling, quality assurance, and statistical analytical procedures for efficient analysis and reporting of status and trends data. This document addresses only the first activity: It presents several concepts regarding the use of indicators in EMAP, as described in the next section. The remaining activities are addressed in other EMAP planning documents currently in preparation or in review.

1.3 PURPOSE OF INDICATOR CONCEPTUAL PLAN

This document is not an implementation plan. Its purpose is to serve as an interim conceptual plan for the indicator component of EMAP as more detailed plans are prepared for each ecological resource. The purpose of this document is threefold: (1) to inform potential EMAP data users of the approach proposed to describe ecological condition; (2) to define a common strategy within EMAP for selecting and evaluating indicators for further testing that will facilitate coordination and integration among six EMAP resource categories (Section 1.4); and (3) to seek expert advice and ecological data sets from the scientific community that are needed to better characterize the spatial and temporal variability of the proposed indicators on a regional scale.

EMAP indicators include indicators related to ecological condition; pollutant exposure and habitat condition; and hazards, natural processes, and management activities. The conceptual basis for these categories and their definitions are presented in Section 2.1.

The indicator approaches in this document grew out of a series of scoping workshops held during summer 1989. The goal of these workshops was not to develop a comprehensive implementation plan for monitoring ecological condition, or even to gain consensus on a list of indicators to be used in EMAP. Instead, their goal was to bring together a variety of disciplinary experts who could establish a point of departure for developing, over a two-year time frame, an implementation plan for monitoring each ecological resource. This strategy will provide EPA decision-makers, other potential data users, and scientific reviewers with an idea about what is meant by "condition of ecological resources," what techniques might be used to measure it, and how these measurements could be used to identify plausible explanations for poor condition where it is discovered.

1.4 REPORT ORGANIZATION AND CONTENT

Section 2 describes a conceptual framework for evaluation and application of indicators in EMAP. Sections 3 through 8 present a rationale for indicator selection for each of six ecological resource categories: inland surface waters, wetlands, forests, near-coastal waters, agroecosystems, and arid lands. Rationales for selecting several types of indicators that could be applicable to some or all of the resource categories are described in Section 9. A rationale for monitoring atmospheric stressors in EMAP is outlined in Section 10. Section 11 summarizes this document and discusses the next steps in the implementation strategy for the indicators component of EMAP. Appendices A through H provide detailed information on the indicators discussed in Sections 3 through 10, respectively, including estimates of spatial and temporal variability, past performance, and levels of cost or effort. Lists of workshop participants and technical reviewers who have contributed their expertise during refinement of the indicator strategy are provided in Appendix I.

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SECTION 2

EMAP INDICATOR CONCEPTS

J.J. Messer[1]

To meet EMAP's first objective (Section 1.2), we must identify indicators of the condition of ecological resources and make unbiased estimates of the regional distribution of values for these indicators for each class of ecological resource of interest. To meet the second objective, we must also define and identify indicators of pollutant exposure and habitat loss or degradation, as well as both human and natural sources of stress that might be associated with poor or changing ecological condition. To meet the third objective, we must establish procedures for analyzing and displaying monitoring data that will be meaningful to decision-makers and the public.

This section proposes a conceptual approach to defining environmental indicators and its relation to the evolving practice of ecological risk assessment. It also addresses some of the problems that must be resolved in implementing the proposed approach and discusses data analysis and presentation of results. The section concludes by defining the indicator selection strategy that was used by EMAP scientists to identify potential indicators and that ultimately will be used to select the most cost-effective indicators for implementation in a long-term monitoring program.

2.1 EMAP INDICATORS

EMAP recognizes three broad categories of indicators (see Figure 2-1):

1. **Response Indicator:** A characteristic of the environment measured to provide evidence of the biological condition of a resource at the organism, population, community, or ecosystem process level of organization.

2. **Exposure and Habitat Indicators:** Diagnostic indicators that are measured in conjunction with response indicators.

   Exposure indicator – A characteristic of the environment measured to provide evidence of the occurrence or magnitude of a response indicator's contact with a physical, chemical, or biological stress.

   Habitat Indicator – A physical attribute measured to characterize conditions necessary to support an organism, population, or community in the absence of pollutants.

3. **Stressor Indicator:** A characteristic measured to quantify a natural process, an environmental hazard, or a management action that effects changes in exposure and habitat.

Response, exposure, and habitat indicators will be measured during annual surveys at sampling sites associated with points on the EMAP grid (Section 2.2). Stressor indicators, by convention in EMAP, are not normally measured at the sampling sites; instead they will be measured in various other ways (e.g., fixed-

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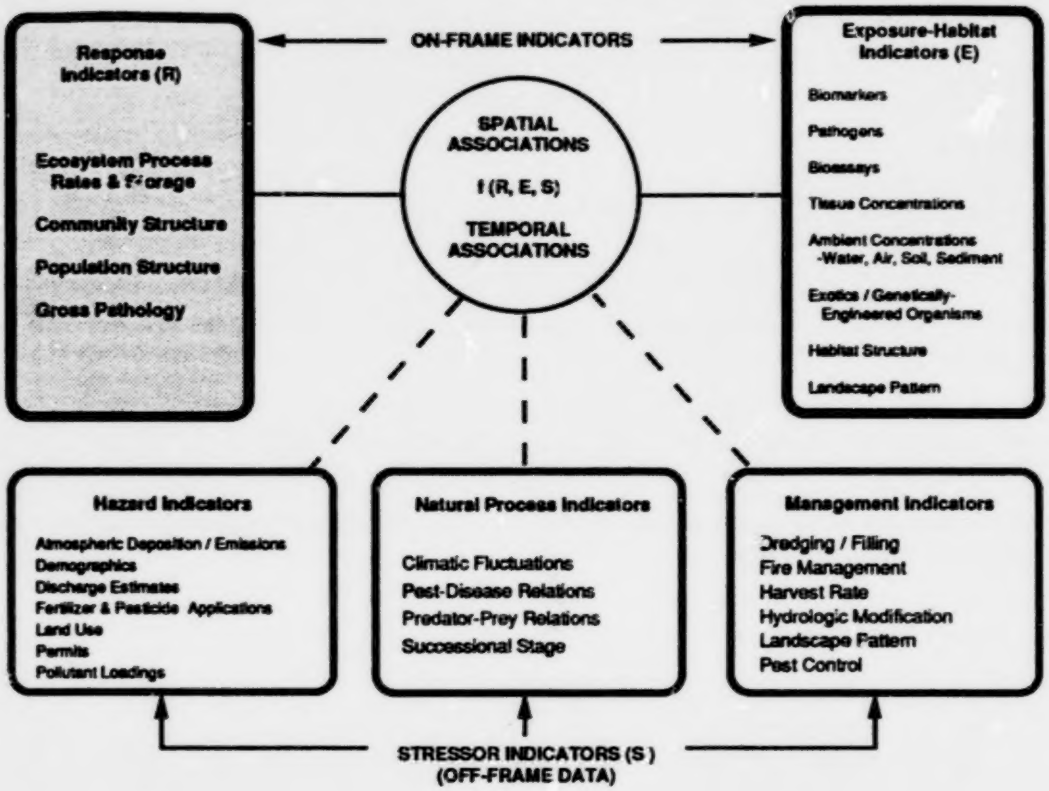

Figure 2-1. **EMAP conceptual strategy. Indicators are characteristics of the environment that, when measured, quantify the magnitude of stress, habitat characteristics, degree of exposure to the stressor, or degree of ecological response to the exposure. The circle indicates that analysis is by statistical association, rather than by explicit (causal) mathematical relationships.**

site networks, inventory, county-level data), usually by monitoring programs other than EMAP. Stressor indicator categories include the following.

Hazard Indicators: Measures that reflect human activities that unintentionally affect ecological resources (e.g., measures of pollutant release, number of permits issued for construction activity, and rates of application of fertilizers to crops and forests that influence nutrient concentrations in adjacent streams).

Management Indicators: Measures that reflect human activities that intentionally alter an ecological resource to meet some management objective (e.g., stocking trout in a mountain stream).

Natural Process Indicators: Measures that reflect cyclic or acyclic phenomena that affect ecological condition, regardless of the presence of management actions or environmental hazards (e.g., natural climatic fluctuations or predator-prey cycles or, probably most common, insect and disease epidemics).

EMAP will rely on response indicators to describe ecological condition, for reasons described in the following section. Statistical associations among the values of response indicators and those of exposure and habitat and stressor indicators, coupled with knowledge about plausible processes and effects mechanisms, will be used to identify possible reasons for poor or changing ecological condition, where they correspond to plausible causal pathways. The selection criteria for all indicators are described in Section 2.4, and examples of indicators for each ecological resource are described in Sections 3-10 and the appendices to this document.

2.1.1 Rationale

EMAP serves two purposes: (1) identifying classes of ecological resources whose condition is deteriorating widely or rapidly (thus deserving of priority attention) and (2) ensuring that the sum total of our environmental protection efforts are achieving the desired results. Traditionally, many monitoring programs have assumed the presence or absence of pollutants is equivalent to poor or good condition. Ecological resources are potentially affected by multiple pollutants, however, arriving in multiple media, and these pollutants interact with management actions and natural processes to exert both population and higher order (e.g., community) effects. The complexity of environmental processes and subsequent effects at regional and national scales makes it unwise to determine ecological condition solely based on indicators of pollutant releases to the environment or compliance with regulations. Nor should we rely on adherence to air or water quality standards or prescriptive targets meant to protect physical habitat extent or quality. For example, lack of toxicity and adequate concentrations of dissolved oxygen are necessary but insufficient to support a healthy fish community if siltation destroys spawning habitat. Conversely, safety factors built into ambient standards or differences in sensitivity among species in situ and laboratory test organisms may sometimes lead to conclusions that healthy biotic communities are present in locations where water quality standards or bioassay LC_{50}'s are exceeded. In fact, response indicators serve as a check, not only on adherence to regulations, but also on the underlying scientific basis of such regulations.

EMAP response indicators must meet one of several requirements. Some indicators chosen to track the success of monitoring programs should be clearly related to aspects of the environment valued by the public (e.g., productivity, biodiversity, recreational value, or "services" performed by ecological resources such as water storage and flood protection by wetlands or cleansing of atmospheric pollutants by forests). Response indicators chosen to identify emerging problems may be less easily perceived as valuable by the public (e.g., stability or resilience), but should be unequivocally linked to the probability of future damage to publicly valued aspects of the environment. Examples of the latter may include shifts in nutrient processing rates in forest soils which presage damage to trees (Likens and Bormann 1979), or changes in zooplankton species that lead to shifts in the composition of the fish community (Brooks and Dodson 1965). Response indicators may be more or less specific to particular stresses (e.g., toxicants, nutrients, acidity, or physical habitat alteration).

While it is critical that response indicators be related to aspects of the environment valued by the public, it is important that they *not* include metrics that are based *solely* on public expectations. One example of such a metric is the degree to which water bodies meet "designated use" criteria, which differ from state to state and may change over time. Questionnaires provide another example: Changing mixes of summer homes and farming activity in rural lake districts may cause a shift in public perception of water quality as lake use changes from fishing and body contact recreation to water storage, even when there is no actual change in the ecological condition of lakes in the region. Trends in public education and degree of expectations regarding environmental quality may mask actual trends in ecological condition or make trends apparent where none exist. Such changes are not a matter amenable to research or risk assessment, but fall into the category of risk management and public policy.

2.1.2 EMAP Indicators and Risk Assessment Endpoints

Risk assessment is the formal framework adopted by EPA to estimate the risks to human health and welfare arising from various hazards and associated mitigation strategies (Yosie 1987, Preisler 1988). Although initially applied by EPA in the human carcinogen area, the risk assessment paradigm is now being applied to ecological risks at various spatial scales (Bascietto et al. 1990; Hunsaker et al. 1990). Ecological risk assessment estimates the effects of human action on a natural resource and interprets the significance of those effects in light of the uncertainties identified in each component of the assessment process. The ideal output of the risk assessment process is an estimated probability that an event of a certain magnitude will occur (e.g., a 90% probability of loss of fish populations in 20% of the lakes in a region; Suter 1990a). The key components of risk assessment include (1) selection of endpoints, (2) qualitative and quantitative description of the sources of the hazard (e.g., locations and emission levels for pollutant sources), (3) identification and description of the reference environment within which effects occur or are expected to occur, (4) estimation or measurement of spatiotemporal patterns of exposure, and (5) quantification of the relationship between exposure in the modified environment and effects on biota. The adaptation of the standard risk assessment paradigm to accommodate ecological risk at different time and space scales has been proposed (Suter 1990a; Hunsaker et al. 1990; Warren-Hicks et al. 1989), and this is currently under active discussion within EPA (Bascietto et al. 1990)

Although the sequence of activities in traditional risk assessment moves from source(s) to exposure assessment and then to effects assessment, an epidemiological approach to ecological risk assessment is also appropriate (Suter 1990b; Fava et al. 1987). It is the latter step in the risk paradigm - effects-driven assessment - that is under development for EMAP. In effects-driven risk assessments, an effect is observed, and one then works toward identification of the hazard or stressors by using exposure information. The degree to which EMAP indicators can be used in a diagnostic manner has yet to be determined.

It is paramount to the success of a monitoring program that the characteristics of the environment being monitored be appropriate for the purpose of the program's assessment goals (National Research Council 1990). The indicators of EMAP share some common characteristics with "endpoints," components of the risk assessment process. Suter (1990a) recognizes two types of endpoints that are used in risk assessments. **Assessment endpoints** are "formal expressions of the actual environmental value that is to be protected." They should have unambiguous operational definitions, have social or biological relevance, and be amenable to prediction or measurement (e.g., a decrease in biodiversity, probability of a >10% reduction in game fish production, or the proportion of raptors killed within a region of pesticide use). The quantitative results of the measurements taken to characterize assessment endpoints are termed **measurement endpoints.** Measurement endpoints must correspond to or be predictive of assessment endpoints. Examples of measurement endpoints include the percentage of trees that exhibit visual symptoms of foliar damage due to oxidants, or the fraction of streams that exceed the LC_{50} for a toxicant to largemouth bass. Many of the criteria for good measurement endpoints for regional assessments (Suter 1990a) were used as criteria for EMAP indicators. In EMAP, the proportion of sites subnominal with respect to particular response indicators within a region are the proposed assessment endpoints.

Assessment endpoints by definition must relate to the environmental values identified for each resource category. Therefore, the measurement endpoints for EMAP are ideally response indicators. Exposure and habitat indicators are not our first choice as measurement endpoints because they do not integrate effects of multiple pollutants or effects of unknown hazards. Occasionally, as in the case of wetland extent, a habitat indicator can serve as both a measurement endpoint and an assessment endpoint, for example, "no net loss of wetlands." Exposure or habitat indicators also could be used to identify possible threats to ecosystems.

The following example describes how EMAP could use a risk assessment framework. The hazard is acidic deposition and its effect on fish in lakes of the northeastern United States. The assessment endpoint in this example is the fraction of lakes that could support brook trout but do not. The measurement endpoint is the distribution of the response indicator, presence or absence of brook trout, in a sample of lakes. Exposure information is provided by both exposure indicators and stressor indicators in EMAP. Exposure indicators could include water pH and calcium and aluminum concentrations. A related habitat indicator could be lake bottom substrate. Stressor indicators could include data on acidic deposition; state fish and game records on fishing pressure, stocking practices, and the like; and meteorological records for the region. If sampling indicates poor condition for fish in northeastern lakes, then the exposure, habitat, and stressor indicators would be used to determine if that condition is associated more strongly with low pH, high aluminum, climate variations, physical habitat disturbance, or acidic deposition.

It is important to keep the purpose of EMAP in mind when considering a risk assessment framework. EMAP response indicators (measurement endpoints) are monitoring tools that need to be primarily anticipatory of environmental effects rather than predictive. EMAP indicators must meet specific criteria associated with annual surveys conducted on probability samples of sites during some index period (see Section 2.2). Because the development of indicators for EMAP is just beginning, the indicators are usually described in terms of a category of measurement endpoints, rather than a specific measurement endpoint. This document identifies important environmental values for each specific resource category (Sections 3-8) rather than specific assessment endpoints. Specific measurement and assessment endpoints will be determined as EMAP core indicators are identified. The indicator strategy for inland surface waters illustrates the development and linkage of measurement endpoints and assessment endpoints (see Tables 4-3 and 4-4).

The type of risk assessment that EMAP could accomplish is likely to be an initial or "screening" assessment, i.e., EMAP indicators could eliminate some possible reasons for poor ecological condition. Additional research and more focused risk assessment would then be required to determine cause-and-effect relationships.

2.2 EMAP DESIGN OBJECTIVES AND SAMPLING APPROACH

To better explain the application of the types of indicators to be used in the proposed indicator strategy for EMAP, the design objectives of the program and the sampling approach required to meet these objectives are summarized in this section.

2.2.1 Definition and Classification of Ecological Resources

EMAP seeks to define the condition of the nation's ecological resources. What are these resources, and how do they differ from "ecosystems"? The word ecosystem usually is used to refer to a local complex of interacting plants, animals, and their physical surroundings, which is generally isolated from adjacent systems by some boundary or "ecotone." An ecosystem could be a watershed or, on a larger scale, an ecoregion or a biome (Shelford 1963; Lotspeich 1980; Bailey 1983). Ecosystems thus may contain forests, lakes, streams, surrounding wetlands, and interspersed agriculture. It is extremely difficult to identify clearly defined target populations of ecosystems, particularly because ecosystems "nest" into poorly defined categories of increasing spatial scale. For this reason, EMAP has classified ecosystems into **ecological resources**, which will form the basis for the reporting units of the program.

Ecological resources are hierarchically organized within EMAP as categories, classes, and subclasses. An **ecological resource category** is the grossest level of aggregation used in EMAP to describe major types of ecological resources: near-coastal waters, inland surface waters, wetlands, forests, arid lands, and agroecosystems. Subdivisions of these categories, termed **ecological resource classes**, represent the largest groups of resources for which strictly comparable response and exposure or habitat indicator measurements can be made. Examples of resource classes include large estuaries, small lakes, emergent estuarine wetlands, oak-hickory forests, sagebrush-dominated shrubland, and orchard cropland. **Ecological resource subclasses** represent a further subdivision within classes, distinguished from other entities in the same class by some additional attribute(s), such as *small seepage* lakes versus *small drainage* lakes. Measurements of extent (numbers, length, area) and indicators will be made on **resource sampling units** (RSUs), which represent the entities that comprise the resource classes. These measurements will provide regional- and national-scale assessments. Reporting on subclasses likely will occur only for special circumstances.

Many of the resource classes are found throughout the nation. In different regions, however (depending on levels of stress, factors that affect susceptibility to a given level of stress, and the success of environmental protection efforts), ecological resource classes may exhibit differences in current conditions and different trends. In many cases, such information will be more useful to decision-makers than data aggregated at the national level. Thus, **regional resource classes** are the smallest groups for which EMAP data are anticipated to be routinely reported. A region within EMAP is qualitatively defined as any extensive geographic area. Regions will generally correspond in size to EPA administrative Regions III through X. Occasionally, subsets of regional resource classes (such as small, *clearwater* seepage lakes with *low acid-neutralizing capacity*) may be identified by post-stratification during data analysis, or before actual sampling for special studies. While special assessments of condition in these subsets may be performed, depending on the urgency of the environmental issue and the degree to which it constitutes a regional or national concern, these data are unlikely to be routinely reported as part of EMAP's annual reports or periodic integrated assessments.

2.2.2 Design Objectives for Resource Classes

EMAP's objectives (Section 1) require that several types of questions for all classes of ecological resources be answered.

- What is the current extent (numbers, length, area) and geographic distribution of each resource class of interest?
- What proportion of each resource class is currently in good or acceptable condition?
- What proportions are degrading or improving, in what regions, and at what rate?
- Are these changes correlated with patterns and trends in environmental stresses?
- Are adversely affected resource classes improving overall in response to control and mitigation programs?

Answers to these questions require a statistically based sampling design that will provide unbiased estimates with known confidence limits for well-defined ecological resource classes (**populations**). Such estimates, which include estimates of extent and current status or condition, are termed **population estimates**. Development of the **sampling design**, or monitoring survey design, requires a strategy that allows sampling of any spatially distributed and identifiable ecological resource without having an explicit sampling frame available (e.g., an explicit list of lakes or all wetlands present in a region targeted for sampling). The design should lead to explicit **probability samples** (samples selected by using probability methods) of resource classes, and also be flexible and adaptive to accommodate the sampling of many distinct resource classes and emerging environmental stresses. The monitoring program objective for each resource class is to describe the current status, and trends in status, of response indicators for that class over regions of the United States. An important additional objective is to determine associations between response indicators and indicators of environmental stress and exposure. These objectives require a probability-based design that enables monitoring for detection of spatial and temporal patterns for each ecological resource, as well as affording some degree of coincidence in sampling across ecological resources.

2.2.3 Making Unbiased Estimates with Known Confidence

The proposed EMAP design strategy uses a systematic triangular sampling grid of points randomly placed over the United States. This grid will enable sampling of ecological resources to produce regional and national population estimates of resource extent, current status (condition), and change over time in extent and status. Landscape descriptions (described below) will be completed for hexagonal areas centered on each grid point; these hexagons are termed **landscape sampling units** (LSUs). LSUs are used to estimate the extent of each resource class and to define implicit sampling frames (e.g, a set of criteria or rules that govern which RSUs are to be included in a target population) for selecting RSUs on which response, exposure, and habitat indicators will be measured. The first sample (**Tier 1 resource sample**) is all RSUs of each resource class within each LSU; it is used to estimate the extent of resource classes (e.g., the number of RSUs or their surface area or total length). The second, or "double," sample (**Tier 2 resource sample**) is a subsample of the first and is used for field sampling of indicators. A sufficient number of RSUs will be sampled annually for each resource class from which regional population estimates are to be made. EMAP currently uses 50 RSUs as a planning target, but this sample size will be adjusted depending on the variance of the indicator measurements within a particular resource class. Specific sample sizes will depend on the precision and accuracy requirements for each class. Tier 1 resource sample measurements are completed each time a new landscape description is acquired, approximately every 10 years. The Tier 2 resource sample forms the basis for annual field measurement of indicators.

The point grid established for the United States is triangular and systematic, with approximately 27 km between points in each direction. A fixed position that represents a permanent location for the base grid is established, and the sampling points are generated by a random shift of the entire grid from this base location. This randomization establishes the systematic grid sample as a probability sample. The proposed base grid density results in approximately one point per 640 km^2, yielding approximately 12,600 points in the contiguous 48 states and approximately 2,400 points and 26 points in Alaska and Hawaii, respectively.

Following placement of the grid, the landscape will be characterized within the LSUs by using a combination of maps, aerial photography, and satellite imagery to define the extent of each ecological resource class. These LSU descriptions constitute a probability area sample of the United States. The probability sample enables regional and national estimates of areal and linear extent of ecological resource classes and numbers of all discrete ecological resources of interest (e.g., lakes or stream reaches).

Indicator measurements for a resource class are taken on each Tier 2 RSU during an **index period** specific to each resource. The index period is the sampling window selected to yield the maximum amount of information during the year; it could vary from one system (and one indicator) to another. Measurements during the index period provide a "snapshot" of conditions during some meaningful time period. For example, a late summer index period may be selected for making measurements on fish populations, when stream flows and dissolved oxygen levels may be lowest and effects of stressors may be highest. Several reasons exist for measuring indicators only during index periods. Because the systematic grid determines the sampling location, RSUs may occur almost anywhere, often on private property or in places where access is difficult. Many of the sites will therefore not be available for intensive or continuous monitoring. Additionally, indicator measurements must be made on a sufficient number of RSUs to make regional population estimates with adequate confidence bounds. With as many as 50 RSUs per resource class and approximately 10-20 resource classes per resource category, cost is a critical factor. Thus, EMAP will operate as a series of annual surveys during index periods.

EMAP's objectives include describing current and ongoing status and detecting trends of ecological condition through the measurement of indicators. These objectives conflict in how samples are allocated in space and time; assessment of status is best done by making measurements on as many RSUs as possible, whereas trend detection is best done by repeatedly making measurements on the same units over time. This conflict is resolved by using a new set of RSUs for each year in four successive years and then repeating the four-year cycle and using exactly the same RSUs as in the first four-year cycle. This **interpenetrating design** is completed so that the same, systematic triangular grid pattern (at one fourth the density) is retained in each year and any particular RSU will be sampled only every fourth year. Based on initial simulation studies, detection of regional and national trends in response indicators on the order of 1% per year is expected to be possible within approximately 10-15 years. Status of ecological condition is estimated annually by using four-year running averages over the four interpenetrating subsets.

EMAP thus will provide statistically unbiased estimates of status, trends, and associations among indicators with quantifiable confidence limits over regional and national scales for periods of years to decades. However, because individual RSUs are sampled only once every four years and 10-15 samples are required to detect a significant trend, EMAP will provide little trend information about the conditions at *any particular site* for at least 40-60 years. Furthermore, the probability-based survey approach in EMAP places important constraints on indicator selection and local interpretation, which are discussed in the following sections.

2.2.4 Extent of Ecological Resources

Quantifying the extent of ecological resources (including numbers, length, area) is important for two reasons. First, we are often concerned with the outright loss of resources, as in the current case with wetlands. Second, we may be more willing to accept a large area in poor condition for an abundant resource than for a limited resource. All resources are potentially at risk, so EMAP will strive to estimate the current extent of specific classes within all six resource categories in the United States. Rare or local resources (e.g., the Okefenokee Swamp or ponds in the Great Basin that support relict populations of pupfish) are best dealt with as special cases.

2.2.5 Current Status of Ecological Resources

EMAP must estimate, for each resource class, what proportion is in good or acceptable condition. As explained in Section 2.1, such estimates should rely on response indicators. Many current indicators have evolved in a bottom-up, or regulatory, environment, and it is likely that others (appropriate in earlier settings) should now be reevaluated. Considerable thought has been given in EMAP to the types of indicators that are appropriate to a "top-down", environmental monitoring approach that seeks to quantify the proportions of resource classes that are in acceptable condition.

2.2.5.1 *Ecosystem Health or Integrity*

Condition has been expressed as "health" or "integrity" in both environmental literature and legislative language, but what is meant by these terms is not clear. Schaeffer et al. (1988) define ecological health, by human analogy, as the absence of disease. Although neither ecosystems nor ecological resources function as "super-organisms," many aspects of a human-ecosystem analogy are useful for illustrating concepts about indicators. Appearances of overt diseased states in humans are familiar: gross pathology, contagious diseases, and trauma, for example, are immediately identifiable and undesirable. In such cases the damage has already occurred. Analogous appearances of ecological "diseases" include changes in the relative numbers of native species, delays in succession, accumulation or loss of biomass, changes in primary production and nutrient cycling rates, loss of nutrients, and changes in stability and resilience. In both cases, causal factors can include pathogens, toxics, genetic damage, and physical injury.

In medical practice, it is common to look for symptoms of diseases that may be in the early stages of development. Human analogs include elevated oral temperature, high or low blood pressure, enzyme imbalances, and indicators of low-level exposure to toxics and carcinogens in body tissues. Symptoms in ecological resources also might be sought that are analogous to symptoms of advanced harm in humans such as drastic weight loss, tumors, trauma, or malaise. Such analogs might include accumulation of toxics in soils and sediments and the presence of toxics, carcinogens, or biomarkers in plant and animal tissues.

Measurements of temperature, heart function, body fluids, and the like must be compared with statistics from populations of normal individuals in order to assess abnormal conditions. Typically, we compare the measurements of symptoms in individuals with expected norms, which may vary among subpopulations (e.g., race, sex). Normal values for ecological indicators also will vary by species and resource category or class, for which baseline data describing reference states must be gathered.

A concept related to health is that of "wellness" in humans, defined as the ability to resist disease or injury. Karr et al. (1986) defined a system as healthy "when its inherent potential is realized, its condition is stable, its capacity for self-repair ... is preserved, and minimal external support for management is needed." The most appropriate term for wellness in ecological resources appears to be integrity. Lack of integrity might be exhibited by symptoms such as low population densities that could threaten mating success, imbalances in trophic levels, or declining ability to buffer changes in nutrient status or pH. Declining integrity also may result from some naturally occurring pathogen or climatic event.

Poor or unacceptable ecological condition thus might be thought of as the presence of advanced damage, symptoms of impending damage, or declining ability to resist damage. We are most interested in conditions that seriously threaten the benefits of our ecological resources (including genetic diversity, recreation, research, flood control, atmospheric buffering) and the capacity of the resources to continue to provide these benefits to society. It is more desirable and cost-effective to strive for maintaining ecological integrity, or at least to detect early signs of damage, than it is to implement controls or mitigation after the damage has reached an advanced state. For many types of damage, however, even though action may come too late to restore an individual resource, signs of current damage can act as a trigger to target efforts toward preventing more widespread damage in the future. This concept is similar to the use of "mortality statistics" in the decision-making arena for public health and safety: Elevated human mortality rates associated with particular regions, diseases, occupations, or activities prompt efforts to be directed more actively toward avoiding future excess mortalities. From this perspective, therefore, even estimating the extent of damage after the fact is a critical concern in EMAP.

There are many challenges to establishing measures of ecological condition that are analogous to human health and wellness. Ecological resources are at a higher hierarchical level than individual organisms; thus evidence of damage and early warning signs at this higher level will inherently be more variable. Furthermore, we must be prepared to judge the health of a resource with respect to certain decisions about management, for example, managing certain landscapes for crop production or commercial timber or certain lakes and streams for stocked fisheries. What is probably most critical for managed resources is that they be as resilient as possible to stressors other than management actions, and that their prior condition would be restored if the management action were terminated.

2.2.5.2 *Distinguishing Nominal from Subnominal Condition*

One of the major tasks in EMAP is determining what value (**threshold**) for a particular indicator is required for a resource to be considered in good or acceptable condition. Subjective adjectives such as "good," "acceptable," "desirable," "undamaged," and "not at risk" can all be appropriate descriptors, depending on the context in which they are used. For EMAP, the more general terms **nominal** and **subnominal** are used to refer to desirable and undesirable conditions, respectively.

If it were known *a priori* exactly what value for an indicator reflected the threshold between nominal and subnominal condition, the percentages of a regional resource class in each category could easily be displayed as a bar graph or pie chart. In reality, however, opinions on the value of the threshold will differ at the outset and will change as more data become available. Consequently, it is important to know the distribution of values for each response indicator for a resource class. Figure 2-2 illustrates how this would be accomplished in EMAP by using a hypothetical cumulative frequency distribution of values for the Index

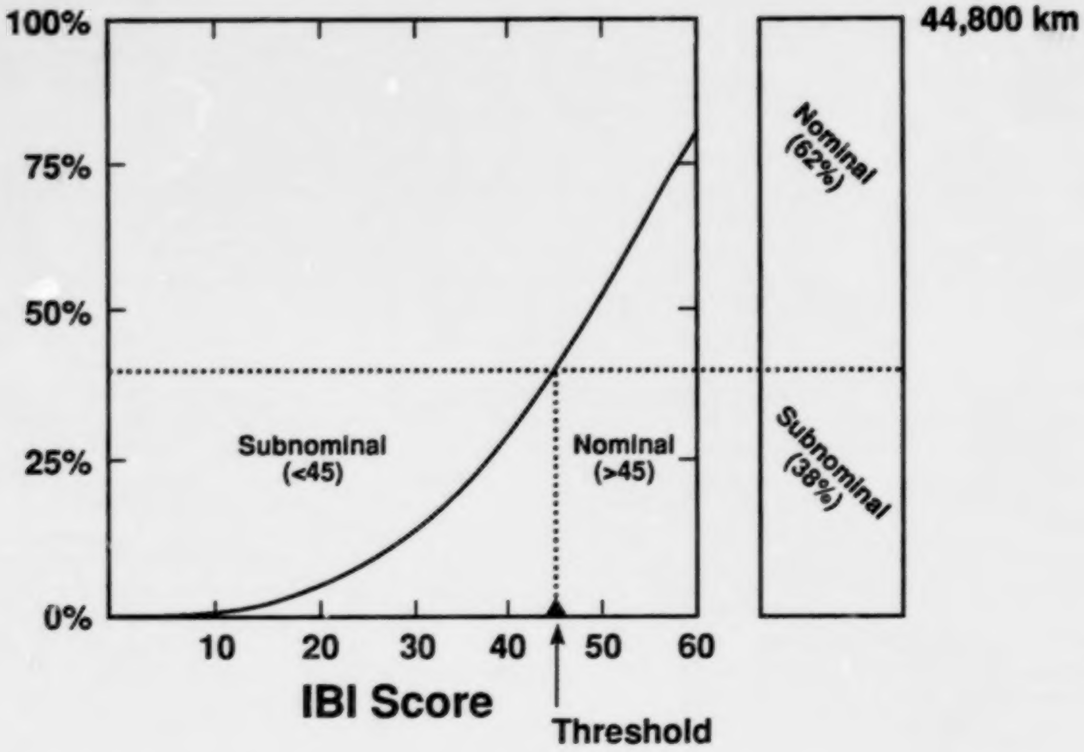

Figure 2-2. Cumulative frequency distribution for the Index of Biotic Integrity in a region, and how it might be used to define the proportion of subnominal streams within a region.

of Biotic Integrity (IBI) developed by Karr et al. (1986), an index that describes the community composition of fish in a regional resource class of streams.

The curve in Figure 2-2 is produced by measuring the IBI for a probability sample of RSUs (e.g., stream segments). If we assume that an IBI score of 45 (see Figure 2-2) is the threshold that separates nominal from subnominal systems, then 38% of the stream kilometers in the region would be subnominal. The height of the bar represents the total number and the total extent (e.g., the number of kilometers) of the stream resource in the region. Separate curves can be constructed for other indicators (e.g., invertebrate species richness or the bottom area covered by filamentous algae). A subnominal score for any individual response indicator measured on a resource sampling unit could make that unit subnominal, or a scheme could be used that would combine indicator values to produce a total score or **index**. Perhaps most important, the proportion of the resource that lay above or below any *previous* threshold can be reestimated as thresholds are modified, or the proportion can be reestimated to examine how changes in threshold values affect the estimated proportion of subnominal resources.

2.2.6 Identifying Possible Causes for Subnominal Conditions

In addition to knowing what proportion of an ecological resource class is in subnominal condition, it also is desirable to know what exposure, habitat, and stressor indicators are correlated with subnominal condition. In a freshwater example of this concept (Figure 2-3), indicators of physical habitat (e.g., hydrologic, bottom,

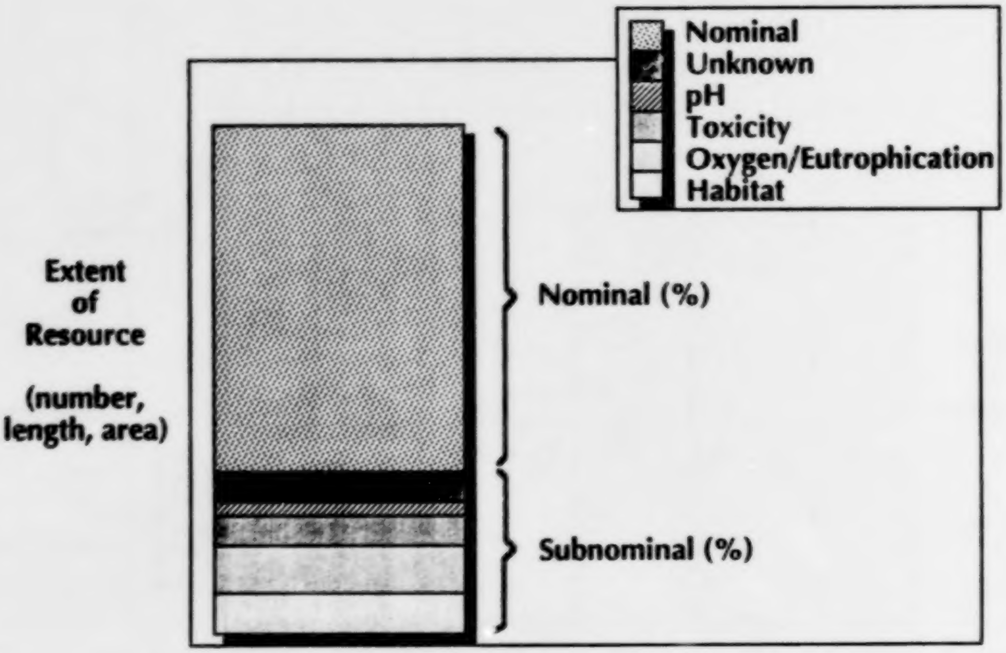

Figure 2-3. Correlative approach to initial partitioning of subnominal systems among possible causes.

and riparian conditions) and exposure (e.g., acidity, sediment toxicity, or hypoxia) were measured. Additional correlations with stressor indicator data on conventional point sources, industrial or mine wastes, nonpoint sources, acid rain, or hydrologic mitigation (e.g., dam operations, consumptive uses) are used to identify possible reasons for poor condition. Statistical expansion, through the EMAP design, enables the number or proportions of subnominal sites in the region to be estimated for each factor that might influence condition, although relative error of the estimate may be high if the number of sampling units representing the subnominal category is small.

Correlations, of course, do not prove causality. If a depauperate fish community is accompanied by poor physical habitat, hypoxia, acidity, or toxic sediments, however, prudence suggests that we begin by seeking the simplest or most obvious explanation. While EMAP's diagnostic capability undoubtedly will be limited early in the program, it will provide an opportunity to conduct correlative analysis of environmental indicators on a regional basis that, in general, does not exist in other monitoring programs. Nonetheless, as shown in Figure 2-3, the condition of some of the subnominal systems is likely to result from one or several unidentified stressors, including resource management, local climatic fluctuations, and natural phenomena; this issue is discussed further in Section 2.3.7. In other cases, subnominal condition might be associated with exposure to more than one pollutant and/or poor physical habitat. Figure 2-3 does not illustrate the possibility of multiple possible causes.

2.2.7 Identification of Regional Trends

By conducting periodic remeasurements of indicators on a sample of approximately 800 RSUs per year (or about 50-60 RSUs for each resource class within a defined region) over a four-year cycle, it should be possible to determine whether statistically significant changes are occurring from year to year and whether these changes represent long-term directional trends, as illustrated in Figure 2-4. The amount of the resource

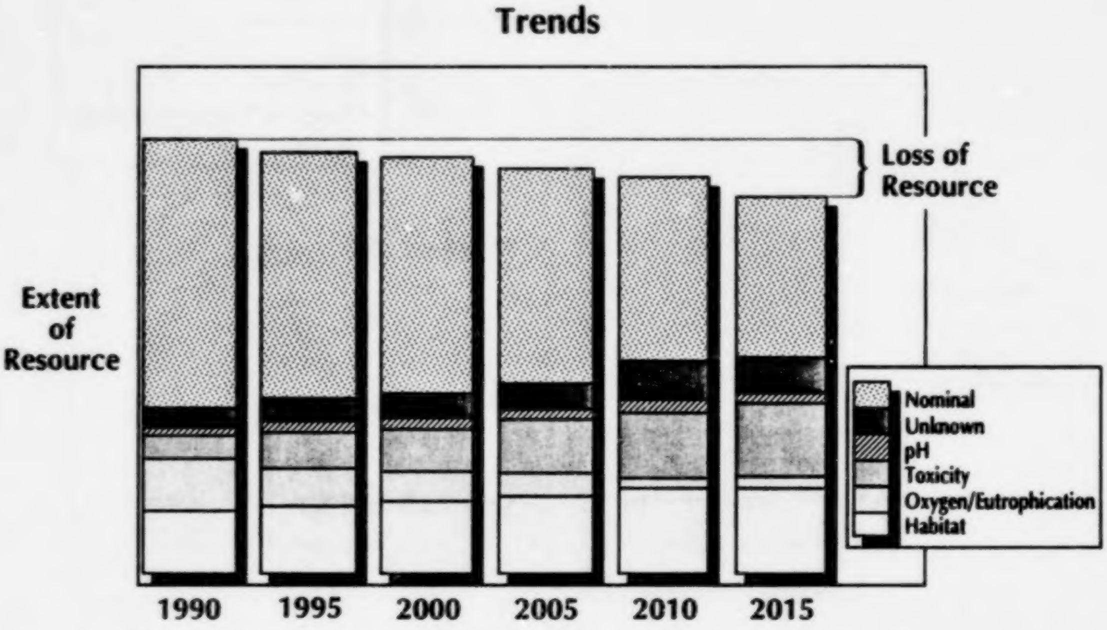

Figure 2-4. Regional trends in the extent and condition of a resource over time.

may change (e.g., stream kilometers may be lost because of channelization or regional drought), the fractionof the resource in subnominal condition may change, and the possible cause or causes (as assessed through correlative analyses) for subnominal conditions may change over time. In this illustration, the reduction in total kilometers of eutrophic streams (as indicated by low dissolved oxygen) is more than offset by the increase in total kilometers that have become subnominal because of pesticides (toxicity) or habitat degradation.

As illustrated for forests in Figures 2-5 and 2-6, the proportions of resource classes in subnominal condition, and the possible explanations for this condition, may vary from one region to another (Figure 2-5) or from one resource class to another within the same region (Figure 2-6). Differences could be due either to differences in stressors or susceptibility to disturbance. Such information can be important in determining the most efficient and effective monitoring efforts. For example, despite the national importance of acid rain as it affects lakes and streams, low acidic deposition rates or alkaline soils and geology make the problem inconsequential in many regions of the country.

2.3 ISSUES REGARDING THE APPLICATION OF THE EMAP INDICATOR STRATEGY

Many issues will need to be studied and resolved regarding the application of the proposed indicator strategy. These issues are discussed briefly in this section. The final selection of indicators will depend on resolving these issues during the design and implementation phases of EMAP.

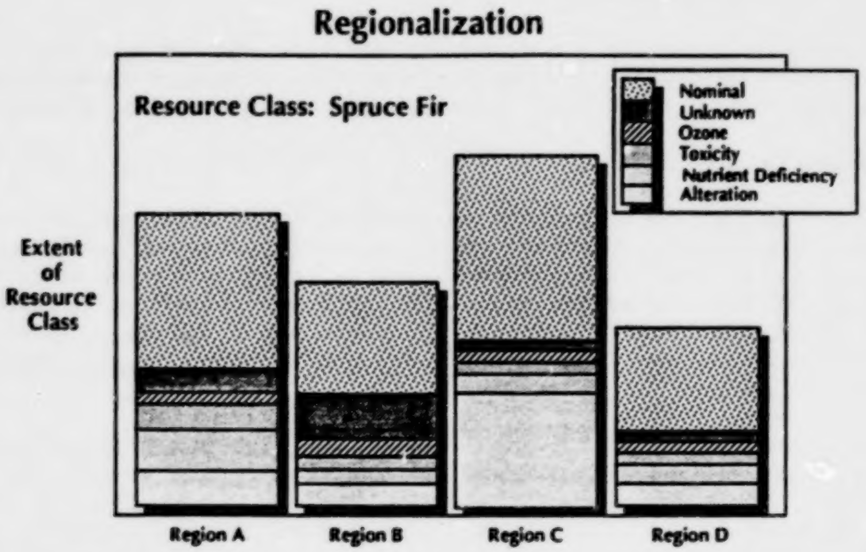

Figure 2-5. Hypothetical comparison of an ecological resource class among four regions. Results of associations of response indicators with exposure and habitat indicators (developed through correlative analyses) are also shown and, in this example, clearly differ among regions.

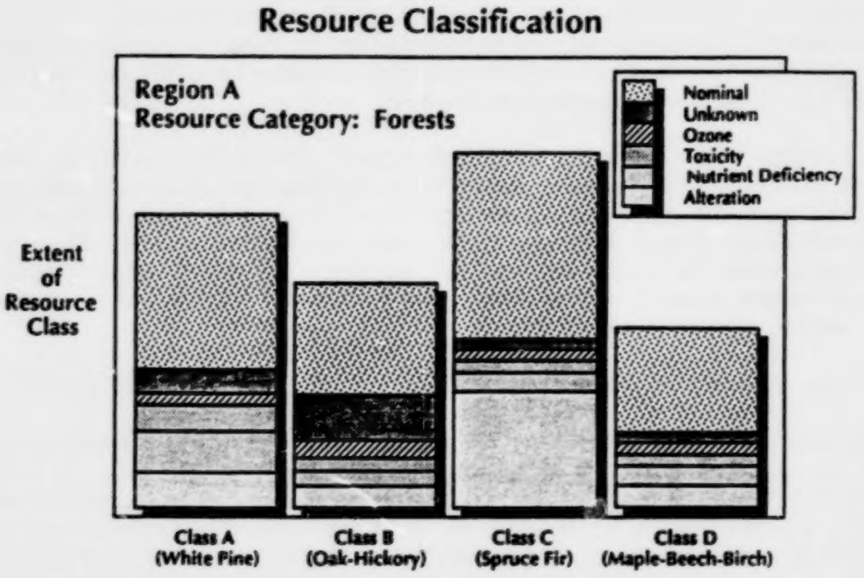

Figure 2-6. Classification of an ecological resource category into four resource classes. Results of associations of response indicators with exposure and habitat indicators (developed through correlative analyses) are also shown and, in this example, clearly differ among subclasses.

2.3.1 Refinement of the EMAP Sampling Design

The EMAP sampling design, as currently conceived, is subject to refinement as more data are gathered. Aspects of the current approach for landscape characterization, the number of resource sampling units selected for measurement, and the possibility of revisiting sites within a given year are discussed below.

2.3.1.1 *Landscape Characterization*

Characterizing all LSUs may prove to be unnecessary in areas of homogeneous topography. Conversely, it may be necessary to increase the LSU density in complex terrain (e.g., in the Sierra Nevada) or in resource classes that have narrow, linear geographic distributions (e.g., the redwoods in the Pacific Northwest). Currently available data are insufficient to determine the density required for adequate characterization at this time. Imagery acquisition is inexpensive relative to interpretation, however, and thus the proposed strategy is to acquire imagery for all 12,600 LSUs, and then to increase the density of LSU interpretation until the resulting precision is adequate.

The current scheme proposed for collecting imagery is to acquire complete national Thematic Mapper (TM) satellite coverage and 1:40,000-scale color infrared photographic coverage for the 12,600 LSUs. Because TM frames contain multiple LSUs, acquiring complete TM coverage of the United States is possible, and interpretation can subsequently be done for any LSU density. Acquiring photography at less than the 12,600 density would result in little cost savings because of the fixed expense associated with flight lines; nationwide interpretation of more LSUs, while possible, is prohibitively expensive at this time. One fourth of the 12,600 LSUs (3,200 nationwide) will be characterized initially. Higher density photography (at an LSU density greater than 12,600) will be acquired only where needed.

2.3.1.2 *Number of Sampling Units and Multiple Sampling*

A target of 50 RSUs per regional resource class is used in EMAP as a planning tool. As both existing and new data are acquired and more reliable variance estimates can be made, this number will be adjusted to meet the design objectives for the various indicators. In practice, setting the design objectives is an iterative procedure that depends on findings from the initial surveys.

To what extent multiple visits to a site can be accommodated or prove to be necessary for some indicators is unknown at this time. While intensive monitoring is precluded and routine seasonal monitoring is extremely unlikely, more than one visit during the index period likely will be necessary in some cases (e.g., to place and retrieve traps or other sampling gear). For some resource classes, more than one index period (e.g., winter and summer for large lakes) may be necessary. For these reasons, providing detailed specifications for the ultimate Tier 2 sampling design, which undoubtedly will vary from one resource category (and class) to another, currently is not possible.

2.3.2 Importance of Scale to Indicators

EMAP is being designed to provide information to decision-makers concerned with national and regional environmental quality. These individuals do not base their decisions on the actions of individual polluters, but, rather, strive to target environmental protection efforts in the most effective way to ensure overall environmental quality across regions or the entire nation. For example, they determine funding allocation among air pollution research or control, point or nonpoint discharges to waterways, or habitat preservation.

Hierarchy theorists suggest that geographic scale is related to time scale (O'Neill et al. 1986). Regional geographic trends thus might best be monitored at seasonal, annual, or longer time intervals. The EMAP sampling design focuses on annual or less frequent surveys conducted during an index period (Section 2.2.3).

One example of using the index approach is to measure fish populations in late summer, when stream flows and dissolved oxygen levels may be lowest and stress may be greatest. These synoptic survey data, collected on a probability sample of RSUs (in this case, stream reaches), will provide an unbiased estimate of how the entire target resource changes over time *during the index period only*. Nevertheless, if the effects of short-term events on aquatic populations (e.g., periods of hypoxia or toxic episodes that co-occur with fish kills or increased drift of invertebrates) are localized and are not detected during the following index period, then the population of subnominal reaches (as indicated by decreased numbers of fish or invertebrates) will remain constant, even if this particular set of reaches (and other reaches, selected for sampling as part of the four-year interpenetrating design) experience such events from one year to the next. Even though the specific reaches at long-term risk from episodic, localized impacts cannot be identified, comparisons among regions of the proportions of resource classes experiencing such risks is possible. If there is a long-term effect (>1 year) from episodic events or if several episodic events result in a cumulative impact that is detectable during the index period, the percentage of subnominal systems will increase over time, assuming other conditions remain constant. In other cases, short-lived but regional phenomena, such as fire or hurricanes, might have widespread ecological effects, but such events usually can be identified from existing data.

O'Neill (1988) also has pointed out that indicators (or state variables) should be of the same hierarchical level if one is to detect or predict associations among them. This means that exposure or habitat indicators that are highly variable in time are probably inappropriate if they are to be compared to response indicators that change slowly, or change over broad geographic areas, or both. O'Neill notes that an exception occurs when the reference-level state variable (endpoint or indicator) is very unstable. In this case, a variable on a lower hierarchical level can cause a "catastrophic" response in the reference level (e.g., a forest stressed by a hard winter may be catastrophically affected by a disease outbreak that normally would only injure a few trees). Although the results of such events may be detected by EMAP, the associated changes in exposure or habitat indicators likely will not be detected.

Evaluation of indicators must account for the variability within RSUs during a given year. In some types of resource classes, within-RSU variability for some indicators may exceed among-RSU variability. In such cases, population estimates will have relatively broad confidence bounds, and the cumulative frequency distribution curves will tend to be flattened. This flattening effect can be reduced by making multiple measurements within an RSU. As discussed in Section 2.3.1.2, whether measurements for any one indicator will be taken more than once per year has not yet been decided, but multiple measurements generally are undesirable from a cost standpoint. The EPA National Surface Water Survey did demonstrate that within-system variability in the chemistry of lakes and streams was much smaller than among-system variability (Eilers 1989; Messer et al. 1988). The variability shown in this survey resulted in cumulative frequency distributions that were quite different among regional classes of lakes and streams, but showed little change between sampling periods.

2.3.3 Definition of a Subnominal Resource

Response indicators will be used to distinguish nominal from subnominal resources. Several approaches to setting threshold values for response indicators may be taken to enable distinguishing nominal and subnominal resources: numeric criteria, reference sites, and classification.

Numeric criteria are based on data not collected as part of the EMAP sampling frame. Examples include a maximum percentage of flounder with tumors collected from a defined near-coastal area or a minimum number of waterfowl in a flyway. Subnominal resources would be those that do not meet such criteria.

A second approach is to measure indicators on regional reference sites, populations of benchmark or control sites that, taken collectively, represent an ecoregion or other broad biogeographic area. The sites, as a whole, represent the best ecological conditions that can be reasonably attained, given the prevailing topography, soil, geology, potential vegetation, and general land use of the region. An example of potential regional reference sites is the long-term ecological research sites (LTERs) designated as resources for the

National Science Foundation's Man and the Biosphere program. Indicator values at these sites could provide initial definitions of thresholds for subnominal condition. The threshold could be based on some statistic (e.g., the estimated upper or lower quintile, 80% or 20%, of the population exhibiting a particular indicator value) for a population of regional reference sites in each region. Estimates could be made of pristine, nominal, and subnominal percentages, if desired.

Another approach is to use multivariate classification techniques on data from the EMAP surveys themselves. In the EPA National Stream Survey (Messer et al. 1988), for example, classification based on multiple chemical indicators revealed groups of streams that were impacted by acid drainage from mines or had unusually low acid-neutralizing capacity (ANC) because of natural geological formations or successional processes of vegetation. In this approach, somewhat simplified by way of this example, classification is used to set a threshold for an index that can be used to compare present and future percentages of subnominal systems on the basis of common criteria. This approach becomes increasingly complicated as the number of stressors acting on a regional resource class increases.

The numeric criteria approach relies on information totally external to EMAP. The reference-site approach would use EMAP data, but might require sampling of a "special-interest" group of sites. Most EMAP scientists currently favor using reference sites, but recognize that the selection of reference sites reflects current professional judgement and thus is subjective. The classification approach would be based solely on data from the EMAP probability sample of the resource classes. There are currently insufficient data to evaluate the general utility of the multivariate classification approach. Despite the current uncertainty, an important consideration is that the definition of a subnominal resource can be revised during subsequent years, and percentages of subnominal resources can be recalculated, provided no new response indicators have been incorporated. For example, in 1995, after revising a threshold based on five years of monitoring data, one might recalculate the percentage of subnominal resources from that originally published for a 1990 survey.

How should multiple indicators be integrated? It is arguable whether any *single* response indicator would put an RSU into a subnominal category. For example, if diatom assemblages and benthic stream communities respond differently to toxics and nutrient enrichment, is the stream nominal or subnominal if only *one* of these communities exhibits subnominal conditions? Is it more subnominal if *both* communities are subnominal? Such questions will be addressed in EMAP through evaluations of the use of indices to describe ecological condition.

It also has not been determined how apparent conflicts between response indicators and exposure or habitat indicators should be interpreted. Situations undoubtedly will arise in which all measured response indicators are deemed to be nominal, but values for exposure or habitat indicators (based on regulatory or other criteria) would lead one to expect the resource to be subnominal. In such situations, the resource may be insensitive (i.e., the criteria for the exposure and habitat indicators may be too stringent), or the resource may be threatened (i.e., the response time of the system is delayed). This issue also will be explored within EMAP as data become available.

2.3.4 Monitoring of Structure and Function

The relationships between structure and function are somewhat elusive. Cairns and Pratt (1986) offered several hypotheses to relate processes (function) and composition (structure): (1) structure and function are so intimately linked that changing one necessarily changes the other, (2) changes in function do not lead to changes in structure, or (3) structure and function seem to be unlinked because analytical techniques are inadequate to identify their connections. Depending on how structure and function are defined, they may not always be inextricably linked.

An evaluation of ecological condition can be based either on current structural measurements or on a projection of future structural changes that result from current activities. In the former situation, monitoring and evaluation of structural characteristics (e.g., macroinvertebrate assemblages, species diversity, population sizes) may be the most advantageous avenue for determining past impacts that have affected ecological condition. For determination of current status and as a means of anticipating problems, monitoring and evaluation of ecological processes (e.g., growth rate, death rate, respiration, primary productivity) warrants further evaluation in EMAP. Schindler (1987) suggested, however, that monitoring ecosystem function (processes), rather than structure, is less likely to provide early warnings of changing condition because feedback mechanisms in natural systems can moderate the effects of perturbations. When possible, EMAP will focus on indicators of structure and will pursue identifying additional indicators of function as appropriate.

2.3.5 Implication of Indicators for Classification

As noted in Section 2.2.6, classification enables estimates to be made for particular resource classes or subclasses (Figure 2-6). In general, we want to compare the condition of resource classes among regions or to identify subclasses that display relatively high proportions of subnominal condition. Such comparison and identification require that indicators be comparable among regions or classes and subclasses.

Certain types of indicators cannot be measured on all resource classes because the organisms are different. Other types of indicators (e.g., zooplankton species richness, nutrient levels) can be measured on any resource, but the data are not comparable among classes (e.g., species richness of zooplankton in lakes versus streams). In other cases, collection or measurement techniques vary (e.g., collecting fish by seining versus shocking). Stratification of sampling (by forest type, stream order, etc.) to compare many kinds of indicator measurements will likely be required.

2.3.6 Use of Non-Frame Data

In some cases, monitoring data collected by other programs may prove to be extremely valuable in describing ecological condition or assessing possible causes through correlative approaches. Some of these data may be collected by using a probability frame and, given that they meet other criteria, they meet EMAP's first objective of providing unbiased estimates of ecological condition with known confidence. In most cases, data collected with a probability frame can be associated with the EMAP sampling frame to provide such estimates. A major effort is ongoing to cooperate and coordinate monitoring efforts with agencies that have probability-based monitoring programs. Examples include the Forest Inventory and Analysis Program (U.S. Department of Agriculture [USDA] Forest Service), the National Wetland Inventory trends program (U.S. Fish and Wildlife Service), the USDA National Agricultural Statistical Survey, and the National Resource Inventory Program (USDA Soil Conservation Service). In many cases, EMAP will likely carry out cooperative sampling by using the EMAP grid to identify sampling sites associated with these programs. To the extent that data are not collected on the same plots, only the population statistical approach described in Section 2.2.3 can be used for assessment.

Data collected on nonprobability frames present a more difficult problem, which has nothing to do with quality or relevance. Examples include acidic deposition data from the National Acid Deposition Program/National Trends Network (NADP/NTN) and water quality data from the National Stream Quality Accounting Network (NASQAN). Both of these networks collect data highly relevant to the EMAP mission (e.g., acidic deposition rates and nutrient export rates from watersheds, respectively), and data quality in both networks is excellent. Neither network, however, provides unbiased estimates of the measured variables over well-defined target resources with known confidence, because the monitoring sites have been located to meet specific needs; this subjectivity could result in unknown biases in the data. At the same time, it would be very expensive (and probably impossible) to reconstruct such networks with a probability design, and replacing them would result in the loss of invaluable time series.

Two approaches might enable effective use of data collected on nonprobability frames. For networks that sample media that are relatively homogeneous on a spatial basis (such as the atmosphere over sufficient averaging times), kriging and some other spatial interpolation techniques can be used to estimate the value of a variable between two monitoring points or an average value for the entire area covered by the network. EMAP proposes such an approach for monitoring exposure to atmospheric pollutants (Section 10) by modifying and supplementing the current NADP/NTN to include additional variables and by either building new stations or relocating existing ones. Networks such as NASQAN that sample discrete entities (streams) whose characteristics do not vary systematically across regions must be dealt with differently. In these cases, models (hypotheses) must be constructed and tested to determine whether such sampling networks yield population estimates that do not differ significantly from those produced by unbiased sampling. EMAP scientists are currently testing these assumptions by using historical data available from NASQAN and the National Surface Water Survey (Messer et al. 1988).

Data such as that from the NADP/NTN can be used in the site-by-site approach described previously if the variance about the interpolated values is not too high. High variance may be particularly problematic in high-elevation areas, around air pollution sources, and along coastlines; the extent of this problem is currently under evaluation. The NASQAN-type data are unlikely to be amenable to an interpolation approach, but they may be quite useful in examining trends in certain water quality indicators.

2.3.7 Use of Stressor Indicators

Stressor indicators, as defined in EMAP, are measures of human activities and natural processes that effect changes in exposure and habitat indicators, which ultimately are related to changes in response indicators. Most stressor data are not likely to be collected as part of the EMAP sampling frame for several reasons.

1. Only a small portion of the land area in the United States is expected to be systematically characterized by higher resolution imagery. Although some types of stressor indicators will be identified and quantified in proportion to their occurrence on the sampling frame, large and sparsely distributed point sources of air and water pollutants that affect regional airsheds or major watersheds are not likely to fall within the LSUs.

2. While habitat data that *represent* local stressors will be characterized from the LSUs, larger or more distant landscape features that extend outside the LSUs must be obtained from other remote sensing sources, possibly involving imagery of coarser resolution.

3. The spatial resolution of data for many stressor indicators (e.g., fertilizer sales and demographics) is counties or other "regional" units, and data of higher resolution are not available. Although it is technically possible, EMAP likely will not be able to duplicate on the sampling frame such efforts that are already occurring in other programs. Therefore, EMAP will make use of existing data on stressor indicators wherever possible.

The use of stressor indicators is partly determined by scale, as noted in item 2 above, but few are likely to lend themselves to site-by-site analyses. Stressor data will be most useful in comparisons among regions or fairly large geographical areas. The quality of stressor indicator data must meet sampling design objectives.

2.3.8 Interpretation and Summarization of Indicators

In addition to the above issues, which deal principally with the selection of indicators and their application to long-term monitoring of ecological condition, several other issues must be resolved regarding how to interpret and present these data once they have been compiled. Resolving the issues described in the following section will help EMAP meet its third objective, which is to report results to the EPA Administrator and the public.

2.3.8.1 *Monitoring and Interpretation of Exposure and Habitat Indicators*

Exposure and habitat indicators should enable the actual threats to the condition of each resource category to be quantified and should enable the major potential threats to be quantitatively projected. Routine exploratory monitoring of exposure indicators (e.g., surveys of all known toxic organics or heavy metals) is probably inefficient, given constantly changing analytical techniques and detection limits and the resultant uncertainty in interpreting data. Routine screening for certain indicators, such as metals or organics commonly associated with other indicators, is desirable, however. Archiving media or tissue samples would allow a more thorough suite of analyses to be performed at a later time and would avoid costly routine monitoring of chemical species that may have little informational content at the time of their collection.

A methodology must be developed to address situations when RSUs in subnominal condition are associated with multiple exposure or habitat indicators (e.g., toxic sediments and habitat structure). Assessing cumulative impacts is becoming increasingly critical if overall environmental conditions are to be improved (Preston and Bedford 1988; CEARC and USNRC 1986). EMAP is to provide information that will help guide funding allocations that might best increase the fraction of resources that are in nominal condition, for example, a decision to target reductions in toxics or air pollutants versus a decision to control some land-use practices. To aid in such decisions, it may be necessary to identify resource classes or subclasses whose condition may not be improved by a single control or mitigation activity (e.g., those impacted by both toxic organics and habitat damage).

In some cases, the suite of exposure and habitat indicators may not be sufficiently comprehensive to provide possible explanations as to why a certain fraction of resource is subnominal. If the size of this "unknown" fraction is very small, not knowing its causes may be acceptable. If, however, the size of the unknown fraction is large or increasing rapidly it may be urgent to increase the effort toward distinguishing the cause or causes.

In the latter case, determining whether the unknown fraction is primarily a result of natural processes such as disease has certain implications for EMAP in identifying those ecological resources most at risk from human-induced stresses. If the resources exhibit natural cyclic behavior and at times experience periods of intense natural stress, these resources could be particularly susceptible to human-induced stresses during select periods of time. Thus, long-term trends in this "naturally" subnominal fraction may provide an important clue to unanticipated effects from human stresses. The unknown fraction overall is expected to be relatively large early in the program, but should diminish as additional indicators are developed and implemented.

2.3.8.2 *Use and Development of Indices*

The application of indices in EMAP, although not yet explicitly defined, represents a long-term research activity that warrants a brief summary here. **Indices** are single values based on mathematical aggregations or combinations of individual indicator values. In most cases, the indicators that are combined are not actually commensurable, i.e., they do not have a common unit of measure. Environmental indices and their properties were thoroughly reviewed by Ott (1978). Washington (1984) presented a specialized review of indices used in water quality studies, and Walworth and Sumner (1986, 1987) reviewed indices used to describe the nutritional status of plants and soils. The IBI devised by Karr et al. (1986) combines a number of metrics describing fish community structure, incidence of pathology, population sizes, and other characteristics to provide an overall index of community integrity. This index differs from earlier indices based on information theory, for example, the Shannon-Weaver (1963) diversity index, in that it reflects what experts believe fish communities should look like according to knowledge of ecologically healthy systems. The index can be customized to different biogeographic areas (Miller et al. 1988).

Indices have particular strengths and weaknesses for assessment. Indices can provide an approximate ranking of RSUs on a "good-to-bad" continuum based on multiple response indicators. A common criticism of indices has been that their use results in a loss of information. If properly constructed, however, the user can examine the original components of the index. Proper construction hinges particularly on the aggregation scheme (Ott 1978). Summing individual response indicator values, each of which is barely nominal, can yield an index value that is more subnominal than it would be in the case when only one indicator is clearly subnominal. Multiplicative aggregation schemes tend to have the opposite effect. Although the future use of EMAP data in developing and testing indices may lead to other aggregation schemes, at this time, the use of the maximum/minimum operators approach (in which the index assumes the value of the worst indicator) appears to be the most appropriate aggregation scheme for EMAP response indicators.

Indices in EMAP could be applied in two stages. First, indicators could be combined into meaningful subindices, but these subindices still may not adequately characterize an RSU. For example, a subindex of visible foliar damage may adequately describe several aspects of leaf pathology, but may reveal little about the vegetative diversity or growth efficiency at the site. In the second stage, indicators and subindices could be combined into indices, and cumulative frequency distributions for the indices could be estimated for the target resource. Unfortunately, multivariable indices have wider confidence bounds about estimates, because each variable in the index contributes to the overall error of the estimate (Cochran 1978). Determining the subnominal threshold for a condition index would not be difficult with maximum or minimum operators (the threshold is determined independently for each indicator or subindex), but it would be quite difficult with indices derived from other aggregation schemes. The maximum/minimum operators option would show not only the subnominal proportion of the population, but also the proportion that is close to subnominal or threatened.

2.3.8.3 *Use of Maps for Data Analysis and Interpretation*

Maps often provide an informative way to examine and explain data. Geographic Information System (GIS) technology facilitates the analysis process by overlaying patterns of exposure, habitat, or stressor indicators onto patterns of response indicator values to reveal important spatial coincidences. Such maps, generated periodically over sufficiently long time periods, are also useful in identifying and displaying changes through time in these indicators. EMAP data could be displayed in several ways, including (1) as individual data points (color-coded, with colors designating particular ranges of indicator values), (2) as bars (with heights proportional to indicator values), or (3) as isopleths (lines connecting discrete points for which indicator values or ranges are the same; for this type of display, the areas between the lines can be shaded). An area on such maps that is dominated by a certain color of points, or the incidence of high or low bars, or some particular shading may signify an area of concern or improvement.

Maps produced from data derived by using a probability frame present some problems. Such problems may not be unique to probability sampling, but may be revealed only when results of probability sampling are available as a comparison. For example, when sampling weights (the expansion factor applied to a probability sample value to obtain a population estimate) are significantly different, a relatively rare entity appears to have the same importance on a map as a common one. As a second example, displaying values from streams of different order or lakes of different size may hide (or create) underlying geographic patterns that can be mistakenly attributed to a stressor rather than a regional pattern in the types of systems sampled. An example is provided by Jager and Sale (1989), who used stream chemistry data from a probability sample of streams in the Southern Blue Ridge. The relationship between ANC of the streams and stream altitude resulted in their predicting low-ANC streams whose relative geographic area was greater than the estimated proportion of the total length of these streams. Both results may be appropriate, according to whether the more appropriate issue is the probability of finding a low-ANC stream or the probable ANC of any stream that is found. Careful analysis of each situation will avoid (or at least identify) such problems in displaying mapped data.

2.3.8.4 *Application of Exploratory Statistics*

Many exploratory statistical techniques can be used with regional data sets. Many examples related to ecological assessments are presented by Green (1979) and Gauch (1982). Cluster analysis can be used to identify classes of sites with similar characteristics that may cause them to respond (or that already have responded) similarly to particular stressors. Canonical correlation analysis can be used to identify multivariate factors that reflect some common characteristic (e.g., a pollutant source) and that can be related to other multivariate factors (e.g., groups of tolerant species). Discriminant analysis can be used to identify indicators that are most closely linked to other indicators in complex sets of data.

Converting data to ratios and other derived forms based on conceptual models also may reveal patterns that do not appear in simple analyses. By analyzing ion ratios related to thermodynamic models in Southern Blue Ridge streams (Velbel 1985), Messer et al. (1988) were able to identify a class of streams representing approximately 75% of the target resource whose chemistry is predominantly controlled by hydrology (dilution).

The range of possible analyses is too great to discuss in detail, but it is critical to note that multivariate statistical techniques also are capable of producing spurious or misleading results. As with mapped data, great care must be taken to avoid incorrect conclusions.

2.3.8.5 *Opportunities for Retrospective Analyses*

EMAP is being designed to establish regional estimates of current conditions against which to compare future trends. Opportunities also exist to compare current conditions against past trends at single sites and over larger areas, where archived remote sensing or other data are available. For example, sediment and tree cores may serve as a record of past changes for comparison with a current regional probability sample. Regional surveys have been conducted that may offer an opportunity for retrospective analysis of regional trends. Such opportunities will be exploited wherever the original data meet minimal criteria for documented and demonstrably comparable methods.

2.4 EMAP INDICATOR STRATEGY

Section 2.1 outlined a conceptual approach to identifying indicators for EMAP. As a first step in implementing this approach, an early version of that section was circulated to the six EMAP Resource Groups. These groups then began identifying and categorizing **candidate indicators** that had been proposed for their respective resource categories over the past three decades, using a combination of literature review, expert workshops, and interviews with managers and scientists knowledgeable about these issues (Figure 2-7). Draft criteria were proposed for identifying the most promising indicators. Although the criteria varied over time and among groups, the groups reached consensus on a final matrix (Figure 2-8). Some of the criteria are critical; others are desirable and *even mutually exclusive*.

Each Resource Group, aided by more than 200 ecologists and resource managers, judged the candidate indicators against the criteria (Figure 2-8). The indicator identification and prioritization process provided critical feedback to the conceptual plan as presented in this section. This entire document was reviewed by 22 external peer reviewers with particular expertise in the various resource categories and by a subcommittee of the EPA Science Advisory Board. Peer review comments resulted in additional refinement of the concept and individual resource strategies. The results of these deliberations, which are summarized in Sections 3 through 9, were used to identify a set of **research indicators** believed to be the most promising for additional evaluation. Research indicators must have well-established, readily standardized methodologies, and a reasonable amount of environmental data should be available. Fact sheets were compiled for these indicators, and they appear in the appendices of this document.

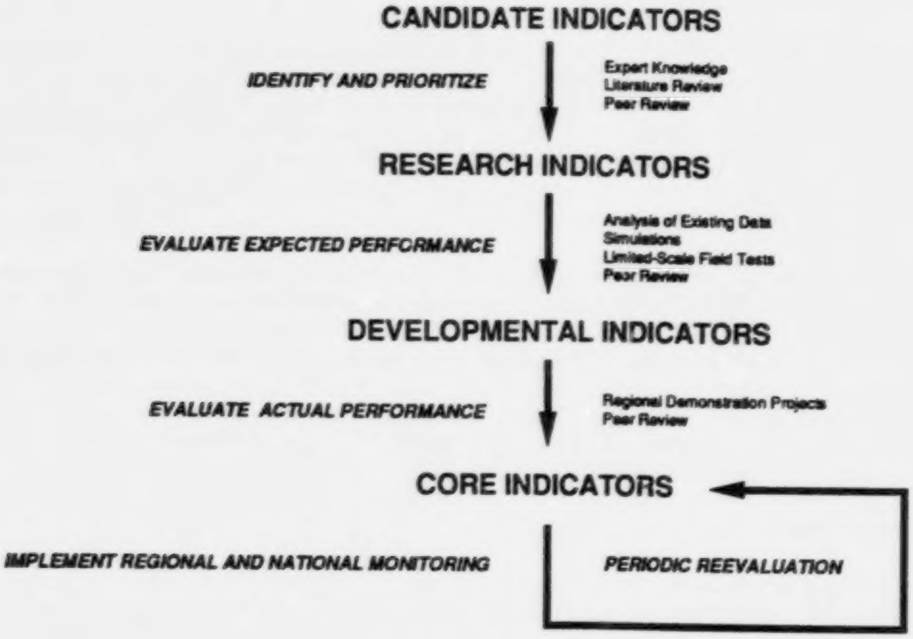

Figure 2-7. Indicator selection, prioritization, and evaluation approach for EMAP.

The next step in the indicator selection process (Figure 2-7) is to evaluate the research indicators; this evaluation is based on analysis of existing data sets, simulation studies representing realistic scenarios and expected spatial and temporal variability, and limited-scale field tests. Those indicators that pass this evaluation are considered **developmental indicators** that are suitable for regional demonstration projects. This process has been completed by EMAP-Near Coastal for estuaries in the Virginian Province, a marine biogeographic province that extends from Cape Cod south to the southern extent of the Chesapeake Bay. Following a peer review, which recommended additional refinements in the strategy, the Near-Coastal Demonstration Project is being conducted in this area in summer 1990. Following evaluation of developmental indicators, based on data from a regional demonstration project, a final set of **core indicators** will be selected for long-term implementation.

Each step in this process requires passing external peer review. Criteria for selecting developmental and core indicators are currently being developed. The number of indicators carried through each step in the process depends on currently available funding. Periodic evaluation of the data will result in careful and deliberate adjustments in the set of core indicators measured. Reprioritization of research indicators is expected to occur periodically as new indicators become available or as new information on previously examined indicators warrants.

We emphasize that the next eight sections present only the first step in the indicator selection process. In addition to explaining the indicator component of EMAP, this document also serves as an important internal integration role in the program and as a mechanism to seek comment, relevant data, and advice from the ecological research community. The latter two objectives are discussed further in Section 11.

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measurement Error[10]	Historical Data Base[11]	**Cost Effective[12]**
Selected as Research Indicators												
A	x	x	x	x	x	x	x	x	x	x	x	x
B												
C												
D												
E												
F												
G												
H												
Considered But Not Selected												
I												

[1] Correlates with changes in processes or other unmeasured ecosystem components.
[2] Is applicable on a regional basis.
[3] Integrates effects over time and space.
[4] Relates unambiguously and monotonically to an environmental value or a relevant exposure or habitat variable.
[5] Can be quantified by synoptic monitoring or by automated monitoring in a cost-effective manner.
[6] Is important to overall ecological structure and function.
[7] Responds to stressors or management strategies.
[8] Is anticipatory by providing an early warning to widespread changes.
[9] Has a standard method of measurement.
[10] Exhibits low measurement error.
[11] Has a historical data base or can be generated from accessible data sources.
[12] Is cost-effective (has low-cost and high-information value).

Figure 2-8. Criteria matrix for EMAP research indicator selection

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SECTION 3

INDICATOR STRATEGY FOR NEAR-COASTAL WATERS

K. John Scott[1]

3.1 INTRODUCTION

The nation's near-coastal waters comprise a diverse EMAP resource category that includes tidal rivers, estuaries, and near-shore waters. EMAP will monitor and assess the condition of ecological resources from the inland boundary of tidal waters out to the continental shelf break. Near-coastal waters are particularly sensitive to anthropogenic input because they serve as critical spawning and nursery habitats for many marine organisms. Estuaries are especially complex and variable and are highly valued by the public. They are also the areas where many anthropogenic inputs are deposited and ultimately sequestered. Most of the U.S. population resides in the coastal zone. It is currently estimated that by the year 2000, 75% of the population will live within 80 km (50 miles) of the coast (U.S. EPA 1988). The continued high-population pressure along the coast poses an increasing threat to these resources.

A series of indicators is proposed in this section for use in assessing the status and trends in the condition of the nation's estuaries. Ultimately, EMAP will also address the condition of continental shelf waters and the Great Lakes. Although part of the near-coastal environment, coastal wetlands and the specific indicators to be measured for them are discussed in Section 5.

A classification scheme was used to subdivide the estuaries into resource classes that have similar physical features and are likely to respond to stressors in a similar manner. Potential classification variables identified for reducing within-class variance in indicator values (obtained from a review of the literature) included salinity, sediment type, pollutant loadings and variables used to infer pollutant loadings (e.g., human population density), and physical dimensions. Salinity and pollutant loadings were subsequently ruled out as classification variables because areal extent of estuarine classes based on these variables could vary from year to year.

A classification scheme based on physical dimension (surface area, length/width) was chosen because physical dimensions:

- change minimally over the time scale of decades and do not adversely influence the value of resulting data to address alternative or "new" objectives;
- allow aggregation or segregation of the data into geographic units that are meaningful from a regulatory and general interest perspective; and
- define groups of systems that can be sampled with a common design and for which data can be aggregated to make meaningful regional and national statements about ecological condition over time.

The three near-coastal resource classes that are currently defined for EMAP are (1) large, continuously distributed estuaries (e.g., Chesapeake Bay, Long Island Sound); (2) large, continuously distributed tidal rivers (e.g., Potomac, Delaware, Hudson Rivers); and (3) small, discretely distributed estuaries, bays, inlets and tidal creeks, and rivers (e.g., Barnegat Bay, Indian River Bay, Lynnhaven Bay, Elizabeth River). The purposes of partitioning estuaries into classes with similar attributes (e.g., size, shape, resource distributions) include (1) a common sampling design can be applied to each class; (2) the within-class variability of indicator values should be less than the between-class variability, thereby reducing the number of samples necessary to characterize a class distribution accurately; and (3) the confidence with which inferences can be made about estuaries that are not sampled is increased.

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What follows is an overview of the rationale for selecting estuarine indicators and a strategy for their application, as well as an approach for refining the indicators proposed for long-term implementation. The topics specifically addressed are as follows.

- Current perceptions of estuarine condition and our identification of environmental values associated with estuaries
- A set of high-priority research indicators and a discussion of why some candidate indicators were not proposed for further evaluation in EMAP
- Additional research indicators that may be incorporated into the set of high-priority research indicators in the near future
- The process proposed for defining the subnominal condition of estuarine resources and how the various indicator responses would be used to identify plausible explanations for subnominal condition
- The role of the 1990 EMAP-Near Coastal demonstration project in evaluating the research indicators and the resultant research priorities for their development and evaluation

3.2 IDENTIFICATION OF INDICATORS FOR NEAR-COASTAL WATERS

3.2.1 Perceptions of Near-Coastal Resource Condition

Some of the most important and productive of the nation's biological systems exist in near-coastal areas, where the majority of commercial and recreational harvests of fish and shellfish occur. Near-coastal areas also provide spawning and nursery habitats for many of these harvested species. Public use of near-coastal systems for recreation generates annual revenues exceeding several billion dollars (U.S. OTA 1987).

Increasing public concern has been expressed over the condition of the near-coastal environment and its ability to support healthy marine organisms. The U.S. Office of Technology Assessment (U.S. OTA 1987) has described the extent of degradation of the marine environment. The pollution of beaches along the northeastearn coast in summer 1988 stimulated extensive coverage of near-coastal environmental problems in the popular press (Toufexis 1988; Morganthau 1988). While the occurrence of medical waste on beaches may not be representative of the seriousness of our coastal problems (Waldichuk 1989), these incidents provide visible reminders that something is wrong. The types of problems in the coastal zone include the failure of about half of the assessed waters to meet designated uses; closure of fisheries due to toxic and pathogenic contamination; low dissolved oxygen (DO) levels in bays and estuaries; and loss of critical habitat for fish, shellfish, and water birds (Hamner 1988). Closure of shellfish beds and declines in commercial and sport fisheries are resulting in significant revenue losses for these industries (U.S. OTA 1987).

3.2.2 Environmental Values for Near-Coastal Waters

The concerns noted above must be related to indicators that can be consistently measured across regions and over time in order to assess status and trends in the ecological condition of near-coastal resources, particularly as that ecological condition relates to public values and expectations. It is, therefore, important to translate public and scientific values and concerns into "assessment endpoints" that can be more directly assessed through the measurement of one or several indicators.

Environmental values associated with near-coastal systems include productivity, biodiversity, and sustainability. Water-column and macrophytic production support the detritus-based benthic food chains in most estuaries. This production also supports most filter-feeding invertebrates, fish, and larval forms of organisms that are abundant in near-coastal waters. Disruption of natural production rates, at a minimum, will result in altered food webs and species composition of higher trophic levels. High biotic diversity is a function of the complex habitat structure and the extreme variability in temperature and salinity regimes typical of estuaries. Maintaining this diversity is critical to the ability of these systems to resist natural and anthropogenic stress.

The public highly values the use of near-coastal waters for commercial or recreational fishing, activities which can be related to the health of fish and shellfish populations. Are these populations present in densities sufficient to make commercial and recreational harvesting feasible? Also, if the fish and shellfish are abundant, are they free of disease and other manifestations of stress, and finally, are they safe to eat? More than half of the population resides or works in counties along the coast. A significant segment of this population is drawn to the coastal areas for recreational purposes, such as boating, swimming, and sightseeing. Floating debris, odor, excessive plant growth, and discoloration alter public attitudes toward water quality. These visible forms of pollution have a strong influence on public perception of near-coastal ecosystem quality (West 1989). In addition to the public value of commercial and recreational fishing, regulatory mandates also exist to maintain and protect other naturally reproducing populations and communities and their habitats (Federal Water Pollution Control Act 1972 and subsequent amendments; Marine Mammal Protection Act 1988; Marine Protection, Research and Sanctuaries Act of 1972).

The environmental values discussed above may be affected by any number of anthropogenic and natural factors. For example, wetland loss and subsequent declines in nursery areas for fishery populations are severely affected by shoreline development. Hurricanes and sea-level rise can also affect shoreline erosion and habitat extent. A challenge for EMAP is to identify plausible explanations of unhealthy conditions. In formulating a strategy to meet this challenge, we considered exposure and habitat indicators that, when used in concert, would broadly identify the possible environmental hazard or hazards, or at least rule out improbable explanations. The major environmental hazards addressed by the near-coastal research indicators are as follows.

- Presence and extent of hypoxic or anoxic waters
- Cultural eutrophication, including both primary and secondary production in the water column and benthos
- Toxic contamination of biological tissue, the water column, and sediments
- Habitat modification, primarily modifications to submerged aquatic vegetation (SAV) and benthos
- Cumulative impacts resulting from interactive effects of various categories of environmental stress

- Emerging problems such as sea-level rise, declines in biodiversity, and introduction of exotic species

3.2.3 Estuarine Indicators Appropriate for EMAP

The goal of EMAP-Near Coastal is to identify a set of indicators that could be used to assess the major hazards or impacts that estuaries and other near-coastal resources are, or could be, experiencing. While it is impossible to anticipate all future hazards, we have tried to select a set of indicators that are related to fundamental estuarine processes. Because measures that address critical public concerns and integrated ecological processes are of particular concern, the focus of EMAP-Near Coastal is on the ecological and biological effects of anthropogenic input, rather than on the documentation of the presence of the inputs themselves (Segar et al. 1987).

The criteria used to select and prioritize near-coastal research indicators (Table 3-1) generally agree with those suggested by others for identifying indicators of environmental quality (Pearson and Rosenberg 1978; Wolfe and O'Conner 1986; Boesch and Rosenberg 1981; Karr et al. 1986; Kelly and Harwell 1989; NRC 1990). A set of research indicators is presented here to stimulate discussion and comment. The set of core indicators to be implemented in the long-term monitoring of near-coastal waters will evolve over the next several years (as described in Section 11).

Work on near-coastal indicator selection began with discussions among EPA-ORD staff in spring and summer 1989. Following preliminary selection and categorization of candidate indicators by the EMAP-Near Coastal team, a series of workshops to identify, evaluate, and discuss candidate indicators of ecological condition and environmental quality was held in December 1989. Workshop participants (see Appendix I) were selected on the basis of recommendations from the Estuarine Research Federation, National Oceanic and Atmospheric Administration (NOAA), and EPA Program Offices and Regions. They included a combination of researchers from private consulting firms, governmental agencies (e.g., U.S. Geological Survey, NOAA's National Marine Fisheries Service, EPA, and state regulatory and resource management agencies), universities and other nonprofit organizations. Participants had a broad range of monitoring experience on all coasts (i.e., Atlantic, Pacific, the Gulf of Mexico) and in a wide variety of marine/estuarine environments (e.g., tidal flats, large and small estuaries, and tidal rivers). Participants were requested to recommend measurement and analysis methods for candidate indicators. Conclusions and findings of the workshops have been incorporated into the following discussions of EMAP research indicators for estuaries. A written external peer review of these indicators was performed in April 1990 (Appendix I.8), followed by a review by the EPA Science Advisory Board in May 1990. A report detailing the near-coastal indicator selection process, including the findings of the associated workshops, will be prepared in summer 1990.

A summary of how some candidate estuarine indicators were judged against the EMAP indicator selection criteria is given in Table 3-1. The identification of certain estuarine indicators as higher priority (Figure 3-1), although necessarily subjective, was based on our review of the literature and experience with near-coastal monitoring programs. High-priority research indicators are those for which sufficient data presently exist to define the sensitivity and reliability of responses to stress with a known degree of confidence. The temporal variability of these indicators over the proposed index period is known, and in general, their responses to major types of stress are understood. A limited-scale field test is needed to further develop standardized protocols for some high-priority research indicators. Those indicators not designated as high-priority either need to have sampling methods developed or have only limited data to evaluate reliability and sensitivity of responses to stress. The temporal variability of responses during the index period is often unknown and must be established as relatively stable before the indicator achieves high-priority status. Comparison of responses among a number of response indicators is necessary to reveal whether they are appropriate and sensitive for determining status and trends of ecological resource condition.

Table 3-1. Evaluation of Some Candidate Indicators for Near-Coastal Waters by EMAP Selection Criteria (H = High, M = Medium, L = Low)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	Cost Effective[12]
Selected as Research Indicators												
Dissolved Oxygen	H	H	H	M	H	H	H	L	M	M	M	M
Benthic Abundance, Biomass, Spp. Comp.	H	M	H	M	L	H	H	M	H	M	H	M
Biological Sediment Mixing Depth	M	L	M	M	M	M	M	M	M	M	L	H
SAV Extent/Density	L	M	H	M	L	H	M	L	M	M	M	L
Fish Species Composition and Abundance	M	H	H	M	L	H	H	L	L	L	M	L
Large Bivalve Presence	H	H	H	M	M	M	H	L	H	M	M	H
Gross Pathology: Fish	M	H	H	M	L	M	M	M	M	L	L	L
Acute Sediment Toxicity	H	H	M	H	L	M	H	M	M	H	L	M
Chemical Contaminants in Sediments	M	H	M	H	M	L	H	M	H	H	H	L
Water Clarity	M	H	L	L	H	M	L	H	H	M	M	H
Water Column Toxicity	M	H	L	H	M	M	H	M	H	H	M	M
Fish Tissue Chemistry	M	M	H	H	L	L	H	L	H	H	H	L
Bivalve Tissue Chemistry	M	H	H	H	L	L	H	L	H	H	L	L
Considered but not Selected												
Deployed Bivalve Growth	M	L	H	M	L	M	M	M	L	L	L	L
Plankton Community Composition	L	L	L	L	L	H	M	H	H	M	M	L
Nutrients	L	H	L	L	H	H	H	H	H	H	M	M
Water Column Chemistry	M	H	L	H	L	M	H	M	H	M	L	L

(continued)

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Table 3-1. (Continued)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	Cost Effective[12]
Fish/Shellfish Pathogens	M	M	L	M	L	L	M	L	M	M	H	M
Biomarkers	M	M	L	M	M	L	M	H	M	M	L	L
Primary Productivity	H	H	H	L	L	H	H	M	H	M	M	M

1 Correlates with changes in processes or other unmeasured components.
2 Applies to a broad range of regional ecosystem classes.
3 Integrates effects over time and space.
4 Relates unambiguously and monotonically to an endpoint, a relevant exposure or habitat variable.
5 Can be quantified by synoptic monitoring or by automated monitoring in a cost effective manner.
6 Is important to the overall structure and function of ecosystems.
7 Responds to stressors of concern or management strategies.
8 Is anticipatory by providing an early warning to widespread changes.
9 Has a standard method of measurement.
10 Exhibits low measurement error.
11 Has a historical data base or the capability of being generated from accessible data sources.
12 Is cost effective (has low cost and high information value).

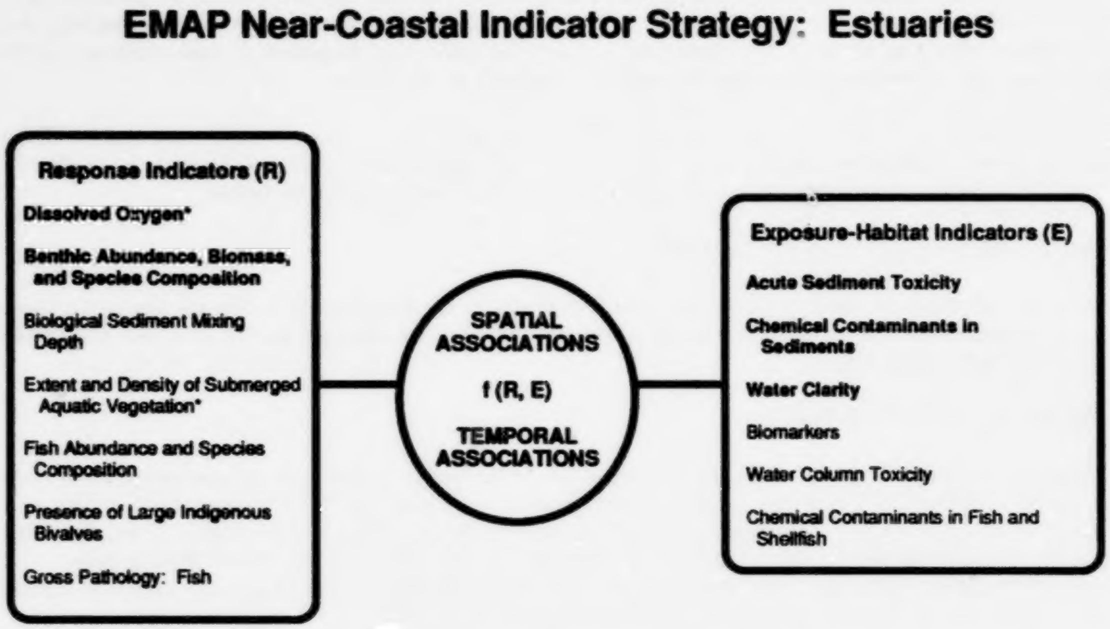
EMAP Near-Coastal Indicator Strategy: Estuaries
Response Indicators (R)
Dissolved Oxygen*
Benthic Abundance, Biomass, and Species Composition
Biological Sediment Mixing Depth
Extent and Density of Submerged Aquatic Vegetation*
Fish Abundance and Species Composition
Presence of Large Indigenous Bivalves
Gross Pathology: Fish
SPATIAL ASSOCIATIONS
f (R, E)
TEMPORAL ASSOCIATIONS
Exposure-Habitat Indicators (E)
Acute Sediment Toxicity
Chemical Contaminants in Sediments
Water Clarity
Biomarkers
Water Column Toxicity
Chemical Contaminants in Fish and Shellfish

Figure 3-1. Diagram of the proposed EMAP-Near Coastal Indicator Strategy for estuaries. Indicators in bold lettering are high-priority research indicators. Response indicators with an asterisk (*) also can serve as exposure and habitat indicators.

The strategy for indicator selection is based on the premise that indicators must relate to assessment endpoints. With the exceptions of oil and natural gas drilling, dredging, and disposal activities, and the limited amount of currently allowed ocean dumping, the major stressors to the near-coastal environment originate on land. Estuarine systems are the repositories of point- and nonpoint-source inputs extending inland from hundreds to thousands of kilometers. Stressor indicators (e.g., land use and discharge estimates) provide information on the magnitude of such sources. Anthropogenic activities represented by these stressor indicators result in a series of hazards, such as contaminant and nutrient loadings and habitat modification, which ultimately produce the major environmental impacts identified earlier. The selected exposure indicators are directly related to types of hazard or impact. The response indicators "respond" to the hazards in a cumulative fashion and thus serve to indicate the overall integrated condition of a marine water body.

All indicators are proposed for measurement during a specific index period, when biological responses to environmental perturbations are expected to be most pronounced. In temperate climates, the warmer, summer months have been selected as the index period for estuaries. Temperature-dependent biological responses to stressors tend to increase dose rates to organisms through higher feeding, filtration, or respiration rates. Metabolic and reproductive rates are also enhanced at higher temperatures, increasing the natural physiological stress on the estuarine organisms. Exposures to anoxic or hypoxic conditions and chemical contaminants will also be higher during summer index periods as a result of high phytoplankton growth and ultimate decomposition and low stream flow or river flow, respectively.

Those research indicators not designated as high priority could eventually provide valuable information on ecological condition, but require additional controlled testing across known gradients before they can be applied in a survey mode. Lower priority research indicators are proposed for additional testing during the

1990 EMAP-Near Coastal demonstration project (Section 3.4). Testing will likely occur at predetermined stations with known presence of contaminants or eutrophic conditions to determine indicator sensitivity, and to compare responses to those of high-priority research indicators also measured at these stations. Some indicators, such as those proposed for fish, will be measured at all stations.

A brief description of each estuarine research indicator is given here. More detailed descriptions of the indicators, their application, suitable index period, variability, and research needs are listed in Appendices A and G as referenced by the code in parentheses at the end of each description below.

3.2.3.1 *Response Indicators for Estuaries*

Response indicators are used by EMAP to quantify and classify the condition of ecological resource classes. Seven response indicators have been selected as research indicators for estuaries, two of which are recognized as having high-priority status.

High-Priority Research Indicators

Dissolved Oxygen. Hypoxic or anoxic conditions are a functional response of the ecosystem to primary production imbalances which can result from excessive nutrient loadings. The measurement of DO as a response indicator would be based on multiple (>6) water-column profiles at each station during the index period. Hypoxic waters would be defined as those having DO concentrations lower than 2 ppm. This indicator would be expressed as the proportion of waters experiencing hypoxia. Associated stressor indicators are flushing rate, nutrient discharge, and loadings data (see A.13, also). (A.1)

Benthic Abundance, Biomass, and Species Composition. This multimetric indicator, proposed for measurement at each sampling station, reflects the ability of the benthos to support bottom-feeding fish populations and to maintain the natural sediment processing features important to nutrient and contaminant flux. The benthic community is also an integrator of overall water quality and may respond to contaminants or to eutrophic conditions as a cumulative response indicator (Pearson and Rosenberg 1978; Rhoads et al. 1978; Sanders et al. 1980; Holland et al. 1987). (A.2)

Other Research Indicators

Biological Sediment Mixing Depth. This response indicator is a measurement of the depth of the oxidized sediment column, as characterized by discrete color changes. An integrative measure, this indicator describes the functional activity of the benthos as it relates to sediment mixing processes; a mature, healthy benthic community is generally inhabited by longer lived, larger infauna. These organisms process, mix, and oxidize the sediment column; and when they are absent, the mixing depth is shallow or absent. The absence of these fauna will restrict the ability of the benthic system to process excess organic matter and contaminants (Rhoads and Germano 1986). Mixing depth measurements would be made with a benthic interface camera (Rhoads and Germano 1982). (A.3)

Extent and Density of Submerged Aquatic Vegetation. This indicator is a measure of SAV acreage and bed density. The root systems of SAV beds stabilize the sediments, and above-ground growth reduces waves and creates a depositional environment. SAV is particularly sensitive to high levels of turbidity and herbicides. Bed outlines and density measurements would be made from visible-color aerial photography. (A.4)

Fish Abundance and Species Composition. This indicator, also a measure of cumulative impacts, would reflect a host of responses to anthropogenic and natural factors; it is expected to integrate the sum of water quality conditions (Weinstein et al. 1980) and would require the extensive use of ancillary variables to interpret changes. Timed bottom trawls would be made at each station on three separate occasions during the index period. After the taxa have been counted and sorted by species, length and weight measurements would be made for selected target species. (A.5)

Presence of Large Indigenous Bivalves. As part of the routine sampling at each station, a rocking chair dredge would be deployed to determine the presence of large infaunal, filter-feeding bivalves. The presence of large filter-feeding genera, such as *Mercenaria*, *Mya*, *Tagelus*, or *Rangia*, indicates the ability of the habitat to support shellfish. This information will be used to design a sampling program to determine shellfish contaminants based on species-specific distributions. The presence, relative abundance, and distribution of these species would be recorded. Selected species would be measured, and tissue samples would be archived for chemical analyses (see indicator A.12). (A.6)

Gross Pathology: Fish. Gross pathological abnormalities in fish are believed to be a response to contaminant exposures. Such abnormalities can also influence the marketability of the affected fish populations. A specified number of each target species is proposed for examination for gross pathological abnormalities (external lesions, fin erosion, cataracts, scoliosis, lordosis, and others). Affected individuals and their flesh tissue would be archived for more detailed histological examination and analysis of chemical residue (see indicator A.12). (A.7)

3.2.3.2 *Exposure and Habitat Indicators for Estuaries*

Exposure and habitat indicators are used by EMAP to identify and quantify changes in exposure and physical habitat that are associated with changes in response indicators. Eight exposure and habitat indicators have been selected as research indicators for estuaries, three of which are recognized as having high-priority status.

High-Priority Research Indicators

Acute Sediment Toxicity. Acute sediment toxicity, like the benthic response indicator (A.2), is also an integrated measure which, in this case, specifically indicates contaminant exposure and potential effects on the benthos (Swartz 1987). This indicator is measured by exposing amphipod crustaceans to sediments from each station for 10 days. Significant mortality in this bioassay indicates a risk to the benthic community, because amphipods are typically the first group of organisms to experience a decline or to disappear from perturbed habitats (Sanders et al. 1980). (A.8)

Chemical Contaminants in Sediments. The selected suite of chemical contaminants in sediments is a direct measure of exposure, which can be related to responses in the benthic community and to acute sediment toxicity. This indicator provides a link to several existing data bases and ongoing monitoring programs, including NOAA's National Status and Trends (NS&T) program. The contaminants on NOAA's list are proposed for measurement in the surficial sediments (top 2 cm) as an indication of recent contaminant input from water-column sources and as an exposure indicator for benthic fauna. The NS&T suite of contaminant measures includes chlorinated pesticides, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), major elements, and toxic metals (NOAA 1987). (A.9)

Water Clarity. In addition to affecting public perceptions of aesthetic value, algal blooms and high suspended particulate loads, and resultant poor water clarity, can have significant biological effects. Poor water clarity impairs the photosynthetic ability of rooted vegetation, algal blooms can result in high dissolved oxygen demands and hypoxia, and suspended solids can lead to siltation and the smothering of benthic fauna. Water-column profiles of light transmission and fluorescence are proposed to be made several times (>6) at each station. Fluorescence measurements would indicate the relative contribution of phytoplankton to reductions in light transmission measurements. (A.10)

Other Research Indicators

Biomarkers. A desirable feature of a monitoring program would be to detect an organism's response to human-induced stresses at the biochemical and cellular level before the stresses produce a detectable response at the organism and population levels. Although the use of biomarkers as early-warning response indicators requires more basic research, their present value for regional survey monitoring is to provide information to support or refute hypotheses on why ecological condition of near-coastal waters is subnominal. (G2.1-G2.11)

Water-Column Toxicity. The proposed chronic toxicity tests are integrated measures of water-column exposure to contaminants and would be related to the responses of the benthic indicators. Three tests are proposed for evaluation: the sperm-cell fertilization test, the red-algae reproductive test, and the bivalve larval toxicity test. The sensitivity of these three metrics would be assessed in selected high-stress and low-stress conditions. (A.11)

Chemical Contaminants in Fish and Shellfish. This proposed set of contaminants is similar to that for NOAA's NS&T program (NOAA 1989). This suite serves as a direct measure of contaminant exposure in the large infaunal bivalves and fish. Whole shellfish tissue and fish flesh would be archived for analysis. The ultimate applicability of this measure is depends entirely on the occurrence and distribution of target fish and shellfish populations as sampled by EMAP. (A.12)

Dissolved Oxygen. Because DO may explain changes in the distribution of benthic or fish communities, it can serve as an exposure indicator as well as a high-priority response indicator. In this case, near-bottom DO measurements would be collected continuously for a 60- to 75-day period. The deployment stations would be selected to represent areas where DO concentrations are expected to be the most variable. This information would be used to define worst-case exposure conditions relative to variability and to establish the minimum deployment duration necessary to characterize the index period. (A.13)

Extent and Density of Submerged Aquatic Vegetation. In addition to serving as a response indicator, this indicator is also a direct measure of habitat modification and loss and thus also serves as a habitat indicator. SAV beds provide spawning and nursery habitats for fish and crabs. (A.4)

3.2.3.3 *Stressor Indicators and Ancillary Variables for Estuaries*

Several types of stressor indicators (those not actively measured on the EMAP sampling frame) will be used to evaluate asssociations among response indicators and exposure and habitat indicators. These measures include natural, economic, social, and engineering factors that can be used to identify possible sources of regional environmental problems. They may include pollutant source measures (e.g., point-source loadings) or land-use and demographic patterns. Other potential stressor indicators include freshwater discharge, atmospheric deposition, precipitation, wind speed and direction, fishery landings, and shellfish bed classification. More detailed discussions of EMAP stressor indicators are presented in Sections 9.5 and 10.

A set of additional, ancillary variables will be collected at each sampling site to provide basic information on the environmental setting. They will be used to normalize values for exposure and response indicators across environmental gradients and to define subpopulations of interest. The ancillary variables include temperature, salinity, water depth, pH, and grain size, organic content, and percent water of sediments.

3.2.4 Estuarine Indicators Not Appropriate for EMAP

Several authors have recommended indicators of ecological health that, while appropriate for other monitoring designs, are not included in the EMAP-Near Coastal strategy (Livingston 1984; O'Conner and Dewling 1986; Chapman et al. 1987; Segar et al. 1987; Taub 1987; also see White 1984; IEEE 1986; Boyle 1987). The constraints placed on indicator selection by the EMAP design include the goal of assessments at national and regional spatial scales, the restriction of sampling to a well-defined index period, and the focus on response in ecological structure and function.

Some indicators were excluded because their short-term or local variability was determined to be too large relative to longer term and regional variability. Measurements of phytoplankton or zooplankton abundance and diversity fall into this category because of the potential for large spatial and temporal variability. Although the planktonic community is a good integrator of water-column phenomena, the spatial variability, temporal variability, and episodic nature of planktonic events are incompatible with sampling once or twice a year during an index period. To address the concern over phytoplankton abundance as related to primary production imbalances, the use of remotely sensed chlorophyll pigment measurements will be evaluated. Chlorophyll concentration as measured by fluorometry could be used as a surrogate for phytoplankton abundance.

Shellfish growth and tissue contaminants, to be measured by using deployed oysters, were seriously considered as near-coastal indicators. It was determined that changes in growth could not be related to a specific environmental problem because of the unknown effects of temperature, salinity, food supply, and food quality variations expected to occur throughout a region. The infection of certain shellfish populations by MSX and other shellfish pathogens was also a concern because of the potential for disease transmittal to uninfected locations. Because of these problems, focus was directed to evaluating indigenous bivalve distribution as a research indicator. Information on contamination in these bivalves will be directly compared with that collected by NOAA's NS&T program. NS&T will provide trends in bivalve contamination for EMAP, and the two approaches will be evaluated during the first year of sampling.

Measurements of water-column contaminants and nutrients were also rejected as appropriate indicators because of the potential for high background (relative to a signal) temporal and spatial variability that results from point sampling. We are not aware of sampling instrumentation that could be efficiently deployed to collect time-integrated or space-integrated water samples for such parameters. In addition, the high cost associated with the logistics of point sampling for water-column contaminants was a prohibitive factor. There is a similar concern over the collection of samples for the water-column toxicity tests, but if some measure related to waterborne contaminants is necessary, the toxicity tests involve much lower costs than chemical analyses and are not chemical specific.

Indicator species, such as those particularly tolerant or sensitive to pollution, are presently not proposed for near-coastal waters. The geographic scope of EMAP appears to preclude their use, even within regions. However, certain functional types of organisms, in the sense of species guilds, may be useful indicators. For example, certain types of benthic species tend to dominate disturbed sites, while an entirely different suite of species tends to dominate unperturbed sites. Some of the characteristics of benthic species that may be useful in differentiating function are short-lived versus long-lived, deposit-feeders versus suspension-feeders, and sediment surface-feeders versus subsurface deposit-feeders. The use of functional types to describe varied benthic impacts within and across regions will be evaluated as data are collected over the next several years.

Another group of common measures that are not included as research indicators is waterfowl and mammal abundance and demographics. The near-term emphasis on estuarine classes prevented a detailed evaluation of waterfowl as a response indicator for near-coastal waters. Monitoring of waterfowl is discussed in Section 9.2. Candidate indicators of marine mammal condition will be evaluated before EMAP is implemented in other regions where these organisms are important, for example, the Californian and Columbian provinces. Indicators of marine mammal and waterfowl health will be examined when the monitoring network expands into off-shore waters of the continental shelf.

3.3 APPLICATION OF INDICATORS FOR NEAR-COASTAL WATERS

3.3.1 Definition of the Subnominal Threshold

Response indicators will be used to distinguish nominal and subnominal near-coastal resources. As described in Section 2, the designation of nominal status may require all response indicators to fall within acceptable ranges. For estuaries, these indicators are DO; benthic abundance, biomass and species composition; biological sediment mixing depth; extent and density of SAV; fish abundance, species composition, and gross pathology; and presence of large bivalves. A quantitative definition of the subnominal threshold for each of the research indicators will be determined during the demonstration project. This definition will account for spatial variability, temporal variability, and measurement error, as well as provide the means for informed judgement as to ecological significance. The numerical thresholds will also be supported by strong correlations with associated exposure, habitat, and stressor indicators. In many cases, the established value may be specific to a particular salinity zone, sediment grain size, or water depth; therefore, parameters may also be used to normalize the numerical thresholds.

Subnominal condition for any single response indicator can be defined by using either external criteria, such as a state regulation for DO, or standards established by comparison with a regional reference site. External criteria that can be used to define subnominal thresholds are available, however, only for their extreme values. For example, a benthic community devoid of animals is clearly subnominal, as is a 100% incidence of pathologies in target fish species. For nonextreme indicator values, which are expected to be the norm, the identification of regional reference sites that are known to be relatively pristine may be necessary. These reference sites may be used to define nominal condition for a defined region. Regardless, subnominal thresholds for any of the response indicators will not be designated until the retrospective analyses of historic data and the analysis of demonstration project data have been completed.

Examples of how the research indicators were assembled to provide some diagnostic capability follow.

3.3.2 Dissolved Oxygen

A site will be defined as subnominal if any of the water-column profiles have observed DO concentrations <2 ppm. Concentrations >5 ppm will be considered nominal, and the intermediate range will be defined as marginal, or threatened. These thresholds are based on available information on DO concentrations that adversely affect estuarine biota (Reish and Barnard 1960; Coutant 1985; Renaud 1986), and most states employ the 5-ppm value as a regulatory standard. These data will be correlated first with values of the benthic and fish indicator responses; under acute oxygen stress, the benthic infauna and fish abundances should be depressed relative to expected nominal values.

Water clarity and chlorophyll pigment data would be indicative of conditions conducive to hypoxia. These data, however, are not expected to be exactly compatible with the DO data since algal blooms and observed hypoxia are not likely to occur simultaneously. Data on nutrient and biochemical oxygen demand loadings (stressors) during the preceding one to two months would provide the most useful diagnostic information. Subnominal areas or classes can also be selected for retrospective analyses by using satellite imagery for estimates of chlorophyll during the preceding spring and summer months. Natural DO depressions, which can result from a combination of high temperature, low flow, shallow depth, and highly stratified conditions, also may occur. Although naturally occurring, such conditions would also be expected to have adverse effects on the benthic and fish communities.

3.3.3 Benthic Abundance, Biomass, and Species Composition

The individual components of this indicator will be expressed as abundance, biomass, or number of species per unit area. Because the subnominal threshold for these metrics will vary with salinity zone, depth, and sediment grain size, the data will be evaluated to determine whether these factors can be used to normalize community parameters across habitat types. Additional data on species composition will be explored to relate species presence and abundance with habitat type and pollutant stressor. These data, however, will be most useful in defining community functional types (e.g., deposit feeding versus suspension feeding, head down versus surface feeders).

This benthic indicator would first be assessed relative to water depth, grain size, and salinity. Subnominal conditions would be reflected by abnormally low or abnormally high abundance or biomass; both factors will usually fluctuate in the same direction. Low numbers of species might also indicate subnominal conditions; alternatively, low species number could be associated with either low biomass and abundance or high biomass and abundance.

Subnominal conditions may result from cultural eutrophication, which may cause shifts in species composition and abundance due to organic loading or direct toxicity due to hypoxic stress. In the case of low DO, organic carbon levels in the sediment (measured as part of the contaminant suite) should be elevated, and the biologically mixed layer (sediment mixing depth) should be depressed. If the subnominal condition is due to contaminant stress, however, acute sediment toxicity should be evident or sediment contaminant levels should be elevated. In either case, certain infaunal feeding types would be associated with stress due to organic loading or eutrophy, and certain sensitive species, such as amphipods, would be absent. Additionally, stressor data would be evaluated as an explanation for subnominal condition - physical stress (e.g., storm or trawl-induced scouring) or climatic conditions.

3.3.4 Fish Abundance, Species Composition, and Gross Pathology

Factors controlling the species composition and abundance of estuarine fish communities are complex and not well understood. However, estuaries with depauperate fish communities or those dominated by pollution-tolerant species will be considered subnominal (Haedrich and Haedrich 1974; Jeffries and Terceiro 1985). While the habitat conditions in a region strongly control the composition of the fish assemblage, polluted areas are thought to exhibit less diverse and less stable fish communities.

Two approaches will be evaluated to develop metrics for estuarine fish communities. The first will involve establishing the species composition expected at each RSU, based on a set of habitat characteristics (e.g., depth, salinity, bottom type) from reference areas. The observed species composition will be compared with that expected to define subnominal conditions. The second approach will employ an integrative measure similar to the Index of Biotic Integrity (Karr et al. 1986). This method, which defines a single value describing the condition of a freshwater community, will require considerable development and evaluation before application in estuarine environments.

The incidence of gross pathologies is expected to be correlated with sediment contaminant concentrations, especially in severely polluted sites (Sinderman 1979; Malins et al. 1988). Various methods will be evaluated to quantify and interpret the incidence of these pathologies in order to establish background or nominal conditions.

3.4 RESEARCH NEEDS

A major research effort is currently underway to evaluate the set of research indicators for estuarine resources. The initial application of this set of indicators will occur during the EMAP-Near Coastal demonstration project to be conducted in the Virginian biogeographic province during summer 1990. One of the primary goals of this project is to apply and evaluate the research indicators presented here. This evaluation includes determining the specificity, sensitivity, reliability, and repeatability of the indicator responses over a broad range of environmental conditions. The application and refinement of sampling methods for research indicators will also occur at this time. A final objective is to demonstrate the ability of the EMAP sampling design and indicator suite to estimate the extent of subnominal estuaries in the Virginian Province. Indicator data will be collected from approximately 160 stations ranging from Cape Cod southward to the mouth of Chesapeake Bay. All high-priority research indicators will be sampled at these stations and at an additional 24-36 "indicator validation" stations. The 24 stations were chosen to represent known conditions of chemical contamination and DO, such that they could be divided into 12 polluted and 12 unpolluted locations. They are also equally divided among three salinity zones (oligohaline, mesohaline, and polyhaline) and the northern and southern portions of the province. Thus, four stations are apportioned to each salinity zone for each biogeographic region. The indicators will be evaluated as to their ability to distinguish nominal from subnominal condition, and to do so consistently across salinity and latitudinal gradients. The other research indicators, with the exception of SAV, will, for the most part, be sampled only at these additional validation stations.

Retrospective analyses of historical data on research indicators to define their respective ranges of values and variability characteristics are ongoing. Analyses that have been completed include (1) Chesapeake Bay benthic data for a number of species and biomass for three salinity zones, (2) Monte Carlo simulations of available fish trawl data for the Virginian biogeographic province to estimate catch probabilities and establish the target species list, (3) regression analyses of contaminant residues in fish from Maryland, and (4) time-series analysis of DO data from long-term deployments in the Chesapeake Bay and Gulf of Mexico. Work will continue on these and other data sets so that these results can be compared and integrated with the Demonstration Project data. These comparisons will focus on components of data variability, precision and accuracy. An evaluation of the effectiveness of the indicator suite is extremely important for the assessment and interpretation scheme discussed in Section 3.3.

Two candidate indicators that have potential as research indicators are chlorophyll pigment and suspended solids. Subnominal DO concentrations would indicate the need to identify algal bloom conditions that may caused the observed hypoxia. An *a posteriori* examination of satellite images for selected RSUs would provide this diagnostic capability. It would also be useful to examine regional-scale suspended solids distributions, particularly as related to riverine flow, storm and runoff events, and the condition of SAV beds. Data for both indicators would be obtained from Advanced Very High Resolution Radiometer (AVHRR) imagery.

In addition to the research issues already discussed, specific research needs associated with the research indicators are as follows.

Dissolved Oxygen

- **Biological requirements for DO.** The definition of subnominal condition requires that critical tolerances of key species be defined.
- **Instrumentation.** Instrumentation needs to be developed that can be deployed for extended time periods (e.g., >7 days between servicing) without sacrificing accuracy or precision.

- **In situ methods.** Development of instrumentation and methods for continuous measurements of chemical species such as ammonia that are typically excluded from monitoring programs because of sampling problems would be advantageous. Instrumentation for continuous, time-integrated water sampling is also a research need.

- **Remote sensing.** As indicated previously, the development and validation of algorithms for chlorophyll pigment and suspended solids estimates would greatly enhance EMAP's diagnostic capabilities. Chlorophyll pigment estimates would indicate the occurrence of bloom conditions that might lead to eutrophication and low-DO events. Unusual runoff and attendant high suspended solids loadings could also be detected in relation to changes in benthic communities and SAV.

Benthos

- **Contaminant bioavailability.** The effects of sediment properties (grain size, organic carbon content, and sulfide concentration) on contaminant availability under natural conditions is largely unknown. Normalization factors that account for the influence of geochemical parameters on availability need to be developed in order to understand potential contaminant effects on benthic infaunal communities.

- **Community function.** Much work needs to be done to establish functional attributes of estuarine benthic species. This information is necessary in order to understand how changes in species composition and abundance affect basic community characteristics such as productivity and habitat structure. Functional attributes can also be used to establish more relevant indices that describe benthic communities.

- **Sediment toxicity tests.** Tests using low-salinity species need to be developed for routine use, and the effects of grain size on the acute test response would need to be quantified. Chronic sediment toxicity test methods should be developed as a more sensitive exposure indicator.

- **Threshold concentrations.** As is recommended for DO, it would be useful to establish threshold levels of contaminants and organic loading that cause adverse biological effects.

- **Deposition rates.** Current data on sediment contamination has no temporal benchmark to identify whether contaminant inputs were recent or historical. The value of sediment contaminant data would be greatly enhanced if sediment deposition rates were known.

Fish

- **Fish species composition.** The relationship between the areal distribution of target species during the summer index period and basic habitat characteristics is necessary to define subnominal condition. The stability of this distribution during the index period will also need to be established.

- **Indices.** The development of community indices similar to those used for describing freshwater resources (e.g., Index of Biotic Integrity) would be useful.

- **Biomarkers.** These indicators appear to have near-term potential as exposure indicators and longer term potential as response indicators. Their use in EMAP would require significant research and testing to distinguish factors that affect response indicators and to establish suborganismal to whole-organism links in biological effects.

- **Sediment toxicity tests.** Good candidates for chronic sediment tests are those life stages of fish that are known to be sensitive and that come in contact with sediments. New methods would need to be developed.

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SECTION 4

INDICATOR STRATEGY FOR INLAND SURFACE WATERS

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4.1 INTRODUCTION

Surface waters are often in a more natural state than the terrestrial or wetland resources they drain. Although lakes and streams can certainly be impaired by land use, they are less subject to drastic environmental perturbations, such as logging and farming of uplands or conversion of entire wetlands. Of course, channel and flow modifications, fishery exploitation, and pollution seriously impair the condition of many surface waters. Nevertheless, streams draining the corn belt of the Midwest, overgrazed rangelands of the West, and clearcut forests of the Pacific Northwest may still retain some species and abundances comparable to those expected of natural habitats, where the channel and riparian zone have not been seriously disturbed. Similarly, lakes in urbanized and farmed landscapes of the Great Lakes states and northeastern United States may maintain trophic states and species similar to those of presettlement times, if runoff and riparian development are controlled.

Although 75% of the earth's surface is covered by water, only 0.02% of the earth's total volume of water is contained in rivers and lakes (Ehrlich et al. 1977). Inland surface waters comprise less than 2% of the conterminous United States by area (Geraghty et al. 1973) - a small proportion that belies their importance for our society. Lakes and rivers provide habitat for aquatic life, sources of drinking and irrigation waters, and locations for recreation, aesthetic appreciation, and navigation. As reflected in the following statements, the integrity of surface water is important to our way of life.

- Inland surface waters provide 79% of the water consumed daily in the United States for drinking, irrigation, and other uses (Ehrlich et al. 1977).
- Water use in seven southwestern states exceeds runoff 9 out of 10 years (Ehrlich et al. 1977).
- Swimming and fishing rank first and second, respectively, among all outdoor participatory sports (USDOI 1989).
- The 31.5 million fishermen who fished inland waters in 1988 spent $329.8 million on their sport (USDOI 1989).

4.1.1 Legislative Mandate for Inland Surface Water Monitoring

Congress passed the Federal Water Pollution Control Act (P.L. 92-500) in 1972, thereby establishing the protection of surface waters as a national priority. The primary objective of P.L. 92-500 was to restore and maintain the physical, chemical, and biological integrity of the nation's waters. An interim goal was to provide for the protection and propagation of fish, shellfish, and wildlife and for recreation in and on the water (Section 101(a)). Several other sections of the Act relate to the protection of aquatic ecosystems.

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Section 105(d)(3) requires EPA to accelerate, on a priority basis, the development and application of improved methods for measuring the effects of pollutants on the chemical, physical, and biological integrity of water. Section 304(a)(1) states that EPA shall develop and publish criteria on the effects of pollutants on community diversity, productivity, biological stability, and eutrophication. Section 305(b) mandates biennial reports that assess the extent to which all waters provide for the protection and propagation of a balanced community of aquatic life.

The Act has been further strengthened since 1972. The Water Quality Standards Regulation (U.S. EPA 1983) requires states to designate uses for aquatic life that are consistent with the goals of the Act, provide criteria sufficient to protect those uses, and establish an antidegradation policy that will protect high-quality waters from being degraded to criteria levels.

The Water Quality Act of 1987 amends P.L. 92-500 and emphasizes ambient standards and assessments as the driving forces behind further pollution abatement. Section 303(c)(2)(B) allows states to adopt criteria based on biomonitoring (a fundamental aspect of EMAP). Section 304(l)(A) requires a list of those waters not expected to attain protection and propagation of balanced biological communities. Section 304(m)(2)(g) requires EPA to study the effectiveness of applying the best available pollution controls for protecting balanced communities. Section 314(a) requires trophic classification of all publicly owned lakes and an assessment of the status and trends of water quality in those lakes. Section 319 mandates identification of waters that cannot protect balanced aquatic communities without nonpoint-source pollution controls.

Other legislation requires assessing environmental risk to aquatic communities. Of particular importance are stressors with potential regional impacts that fall under the Federal Lands Policy and Management Act (FLPMA), the National Environmental Policy Act (NEPA), the Resource Conservation and Recovery Act (RCRA), and the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA). In addition, the Endangered Species Act mandates assessments and protection of rare and threatened species, and the National Forest Management Act of 1976 requires conservation of vertebrate diversity.

4.1.2 Limitations of Current Inland Surface Water Monitoring Programs

Despite the legislative mandate to protect aquatic life, the responsible federal agencies have not adequately assessed either the status of ecological resources or the overall progress toward legally mandated goals of mitigating or preventing adverse ecological effects. The Study Group on Environmental Monitoring (NRC 1977) stated that EPA monitoring programs (1) did not provide data needed to predict the effects of management decisions, (2) did not assess long-term environmental changes, and (3) focused on pollution sources rather than discovery and prediction of environmental problems. This group recommended that EPA conduct long-term monitoring of natural and impacted ecosystems to evaluate environmental effects. The EPA Science Advisory Board's Ecology Committee (SAB 1980) further recommended that the agency increase its biomonitoring activities.

In 1981, the U.S. General Accounting Office (U.S. GAO) concluded that EPA's water quality monitoring program was inadequate (U.S. GAO 1981). This conclusion was based on the small number of samples and infrequent sampling periods, lack of statistical and ecological representativeness, and inability to associate problems with causes. Seven years later, GAO (1988) concluded that EPA still needed to improve its ability to measure the environmental results of its regulatory programs. GAO observed that EPA rarely used biological community measurements of quality and had reduced its monitoring activities in recent years. In addition, data collected by EPA were not easily accessible and made analysis of status and trends difficult because of limited monitoring coordination, unsuitable network design, and data incompatibility.

The Agency itself has also recognized deficiencies in its surface water monitoring programs. A monitoring strategy produced by EPA's Office of Water (U.S. EPA 1984) stated that EPA's fixed-station network had insufficient statistical reliability to support national assessments. The strategy also concluded that biological monitoring needed more emphasis and that waters not known to have problems should be evaluated. Nonpoint-source impacts and controls were essentially unknown, the environmental effects of source controls were not assessed, available data were not properly integrated, and national studies were needed.

Three years later, the same concerns were expressed (U.S. EPA 1987a): Increased biological monitoring was needed to characterize ecosystems and identify problems and trends, better data were needed to determine if pollutant controls were achieving the desired results, data on the effects of nonpoint-sources were lacking, less expensive problem-screening and trend-monitoring methods incorporating biological techniques were needed, greater consistency in monitoring and reporting were required to create sound national evaluations, and too little ambient monitoring had been conducted. The Agency clearly needed a national monitoring framework with well-defined objectives and guidance.

Finally, the Agency concluded that biological criteria and biological and physical habitat monitoring were needed to assess the impacts of nonpoint-source pollution and controls. This conclusion was reached because of the typically nontoxic, episodic nature of nonpoint-source loading and the extent of the problem (76% of impaired lakes and 65% of impaired rivers result from nonpoint-source pollution, predominantly agricultural; U.S. EPA 1989a).

Given the unambiguous legal mandate and the periodic internal and external reviews and recommendations, it is obvious that our current approach to surface water monitoring must be changed. A comprehensive framework that supports regional and national assessments, incorporates sound statistical survey designs, and focuses on biological indicators of resource condition is needed. Such a framework would also be useful to other federal agencies that monitor freshwater resources.

4.1.3 Inland Surface Water Resource Classification

A number of different classification schemes could be used for lakes and streams based on formation (e.g., lake type), fisheries use (warm water vs. cold water), dominant terrestrial vegetation (streams in forested or agricultural regions), and extent. For lakes, this classification will have little influence on the discussion of appropriate indicators and methodologies; however, size distinction can be important when discussing indicators for streams and rivers. While the taxa which are sampled in streams and rivers may be the same, the appropriate indicator derived from the field metrics and the sampling methodologies are likely to be quite different for small versus large systems. For inland surface waters, the issue of resource extent is an important consideration at the class level because the standard rules for selecting a representative lake or stream segment within a landscape sampling unit tend to favor smaller systems because they are more numerous. There are, for example, twice as many lakes in the 1- to 4-ha size range as there are in the 4- to 2000-ha range; similar statistics occur for stream size. To balance the inclusion of different size systems in the final sample, it is necessary to use size as the initial classification criterion.

The initial size boundaries of lake and stream classes will be somewhat arbitrary, but will eventually be related to their respective size distributions. Reservoirs will not be distinguished from lakes because doing so on the basis of characterization information is difficult; also, in many cases, lakes and reservoirs function similarly.

Because large lakes (>2000 ha) are relatively scarce (200-250 in the continental United States), they will be censused. Smaller lakes can be sampled with the grid design. A division of lakes into three size classes, 1 to 10 ha, 10 to 2000 ha, and greater than 2000 ha, appears to be sufficient. Streams also will be classified by size and initially partitioned into two classes: (1) small streams sampled from a grid frame and (2) large streams that will be censused.

4.2 IDENTIFICATION OF INDICATORS FOR INLAND SURFACE WATERS

4.2.1 Perceptions of Inland Surface Water Condition

Although freshwater resources may support rich biotic communities compared to the intensively managed terrestrial resources they often drain, many of these resources have been significantly affected by anthropogenic activities, as demonstrated by the following information.

- Twenty-five percent of the threatened and endangered species of Oregon are aquatic (U.S. Fish and Wildlife Service 1986).
- Twenty percent of the native fishes of the western United States have become extinct or are endangered (Miller 1961).
- Thirty-two percent of the native fishes of the Colorado River basin are extinct, endangered, or threatened (Carlson and Muth 1989).
- Since 1910, annual Columbia River salmon and steelhead runs have declined by 75-85%, which represents 7-14 million fish (Ebel et al. 1989).
- The Missouri River commercial fish harvest has been reduced by more than 80% since 1945 (Hesse et al. 1989).
- Thirty-four percent of the native species of Illinois fishes have been extirpated or decimated (Smith 1971).
- Since 1850, 67% of the fish species from the Illinois River and 44% from the Maumee River have declined or disappeared; in small or medium-sized streams, the percentage of species lost ranged from 70 to 84% (Karr et al. 1985).
- Since 1933, the Tennessee River system has lost 20% of its mollusk species (Isom 1969), and 46% of the remaining species are endangered or seriously depleted throughout their ranges (Jenkinson 1981).
- One hundred ninety-nine fish species (27% of the fish fauna) in the United States are endangered, threatened, or of special concern (Williams et al. 1989).
- In the past 100 years, 40 North American fish taxa have become extinct, 19 since 1964 (almost one per year). The most common contributing factors were habitat loss (73%) and introduced species (68%) (Miller et al. 1989).
- Thirty-eight states reported closures, restrictions, or advisories relating to fisheries in 1985 (Moyer 1986).
- The ecological risks of physical alteration of aquatic habitats and point- and nonpoint-source discharges were ranked as the second and third most serious environmental threats in a survey of EPA scientists (U.S. EPA 1987b).

Similar information on other aquatic biota are virtually unknown at this time. Although this information implies serious and widespread biological impairment, EPA estimates that criteria for designated beneficial uses were met in 74% of the river miles and 75% of the lake acres evaluated (U.S. EPA 1987b). This apparent contradiction may result from inappropriate or inconsistent use designations, unsuitable ecological indicators and assessment criteria, or inadequate monitoring designs. Thus we require a national monitoring framework with appropriate biological indicators for inland surface waters to resolve these apparent contradictions and to provide baseline data for future assessment and management decisions.

4.2.2 Environmental Values for Inland Surface Waters

To be effective, monitoring programs must provide data that can be related to an assessment endpoint, an example being the degree to which the designated beneficial use of an aquatic resource is achieved. Criteria for meeting a designated use are attained if the system is being used for its intended purpose, such as maintaining habitat for aquatic life, fishing, water sports, aesthetics, navigation, or water supply. Use designation has been ineffective for protecting biological integrity because many designated uses, as well as the criteria used to assess use impairment, have little relationship to ecological condition. Often the uses are imprecisely defined. For example, maintenance of "warmwater fish" or of "fishable" water may be considered attained whether the water supports a few carp or a large number of smallmouth bass, and "aquatic life" may likewise mean blue-green algae or arctic char. It is also quite possible to have excellent fishing and impaired ecological condition or vice versa.

An alternative to "designated use" as an environmental value is the protection of biological integrity, mandated in P.L. 92-500. Biological integrity, although not defined by the legislation, means "a balanced, integrated, adaptive community of organisms having a species composition, diversity, and functional organization comparable to that of natural habitat in the region" (Karr and Dudley 1981). Two states, Maine and Ohio, have developed quantitative biological criteria based on this concept of biological integrity. Maine's biological standards for Class A (highest quality) waters consist of specific values for six macroinvertebrate indices, based on conditions in naturally occurring reference communities and assessed by using a dichotomous key (Courtemanch and Davies 1988). Ohio EPA (1988) used reference sites to set numerical criteria, specific to ecoregions and stream size, for two fish assemblage indices and one macroinvertebrate index.

It is generally recognized that an understanding of what constitutes biological integrity or impairment cannot be determined a *priori*. Rather, this understanding depends on knowing the acceptable range of values for measured components of the system. In practice, therefore, integrity or impairment is determined by an evaluation of indicator scores. Defining integrity and impairment thus depends on choosing appropriate indicators and determining their expected or acceptable values. The selection of indicators should be influenced by our knowledge and perception of the critical components and processes within an ecosystem that best define the ecosystem's attainable structure and function.

At least two philosophically distinct approaches exist regarding assessment endpoints and indicators of ecosystem integrity. The first is to define biological integrity based on the presence of specific characteristics of interest, implying that one can identify and quantify such a set of measurements. The second is to define biological integrity based on the absence of known problems. This second approach recognizes that in many instances one does not know exactly what the system should look like but can readily identify what it should not look like. These two approaches, which present slightly different perspectives, should not be viewed as conflicting, but complementary.

4.2.3 Hazards to Inland Surface Waters

Current hazards to inland surface waters fall into nine categories, some of which are related to land use and pollutants, and some of which are related directly to resource management.

1. Cultural eutrophication (anthropogenically induced nutrient enrichment)

2. Contamination (both point and nonpoint, as well as toxic and nontoxic)

3. Atmospheric stressors (e.g., acidic deposition and toxics such as herbicides and polychorinated biphenyls)
4. Habitat alteration (physical structure and substrate)
5. Flow modification
6. Thermal alteration
7. Species introduction
8. Harvest imbalance (overstocking or overharvesting)
9. Global climate change

Perturbations within each of these categories potentially threaten surface water condition, either in the context of traditional concepts of beneficial uses or of ecological condition.

Cultural eutrophication can result in aesthetic degradation of streams and lakes by inducing the formation of surface blooms of noxious blue-green algae, which also contribute to taste and odor problems in drinking water. Additional problems can result if aquatic macrophytes reach such magnitude that they interfere with boating and swimming. A very serious ecological consequence of accelerated eutrophication is the alteration of fish populations via changes in the plankton community or as a result of oxygen depletion.

Contamination of fish and shellfish by heavy metals and synthetic organic chemicals is of obvious concern to fishermen and consumers, as is the presence of fish lesions and tumors. Less apparent but equally important are the toxic effects on nongame components of aquatic and semiaquatic animals. Although acute effects such as fish kills are obvious, chronic effects can result in loss of desirable species and domination of communities by tolerant, undesirable, and nuisance species.

Substances deposited as a result of anthropogenic emissions may act as nutrients (e.g., nitrogen) or as contaminants (acid rain, toxics). Atmospheric stressors are listed as a separate hazard category because they are regional in extent and are not related to the permitting process used by states to protect water quality.

Physical habitat alteration is one of the most serious hazards to inland surface waters, particularly rivers. It includes direct channel modification (dams, channelization) and indirect effects of land use (loss of natural riparian vegetation, sedimentation). Channel modifications may improve some designated uses, such as navigation and water supply, but barriers and loss of habitat diversity usually result in fewer or different native species and increased populations of exotics. For example, loss of riparian trees and shrubs decreases cover, increases sedimentation and turbidity, and changes the food base from leaves to algae. The fauna subsequently can change, for example, from one characterized by smallmouth bass and mayflies to one that is characterized by carp and worms, and losses in fishing quality and changes in natural diversity and composition occur.

Through drainage and diversion, flow modification may result not only in the direct loss of aquatic resources but also the loss of all uses and species dependent on them. Removal of vegetation, urbanization, and water projects may also disrupt ground water recharge, lake water levels, and the timing and magnitude of flood and low flows. Streams become less suitable for boating and aquatic life, and lakes develop unappealing "bathtub rings."

Cooling water discharges or removal of riparian vegetation may result in thermal pollution. The former may result in fish kills (depending on the ratio of effluent to receiving water) or, more often, changes in species composition and production. Removal of riparian vegetation typically has a chronic impact by altering the food base and physical habitat. In cold-water systems where food is not limiting, elevated temperatures may increase fish production. However, if food is limiting or if species are near their thermal limits, fish production decreases and species are eliminated.

Introduced species, whether desirable game fish or nuisance plants and animals, often create problems. For example, the Asiatic clam and zebra mussel often clog water intake structures; water hyacinth and Eurasian milfoil interfere with boating. Introduced species, which may outcompete or prey upon native species, are usually extremely difficult to eliminate.

Overharvest of fish and shellfish is responsible for decreased sizes of individuals and populations and thus decreased reproductive rates. Overharvest of larger game fish individuals and species is implicated as a cause of the stunting of sunfish in lakes. Fishing pressure on large carnivorous game fish is associated with increases in their less desirable competitors and prey.

The potential impacts of global climate change on aquatic conditions are virtually unknown, but the potential change as a result of this perturbation is of an unparalleled magnitude.

4.2.4 Inland Surface Water Indicators Appropriate for EMAP

The process of selecting ecological indicators for inland surface waters was based on ongoing research in EPA's programs on aquatic toxicology, acid rain, and ecoregion/biocriteria programs, all of which share some goals with EMAP. Important activities in developing a suite of research indicators for inland surface waters are listed in Table 4-1. A written external peer review of these indicators was performed in April 1990 (Appendix I.8), followed by a review by the EPA Science Advisory Board in May 1990. EMAP workshop participants are listed in Appendix I.

Four general criteria were used for selecting response indicators for inland surface waters. Although listed individually, it is important not to think of each indicator in isolation. Rather, they should be considered as a suite of tests used to estimate the health of surface waters with acceptable levels of uncertainty.

- The indicators must be biological and incorporate elements of ecosystem structure and function. An indicator should correlate with changes in other unmonitored biological components and should incorporate changes in predation, competition, life histories, natality, mortality, and migration without directly measuring these rates. Also, indicators applied to lakes should be interpretable at several trophic levels.

- The indicators should be socially relevant. There must be clear connections with environmental values, and they must be responsive to the individual or cumulative effects of a broad array of potential stressors. An ideal indicator is applicable in a broad range of surface water types across the nation. Finally, it should provide early warning of detrimental ecological change or indicate the early stages of recovery.

- The indicators must be sensitive to varying levels of stressors, but not to the degree that they produce false alarms or excessive noise. In fact, they should be insensitive to acceptable, natural variations or at least useful for distinguishing unacceptable and acceptable situations. Another useful feature is sensitivity to important episodes that do not coincide with the sampling period.

- Useful indicators are cost-effective, providing considerable information in a limited amount of sampling time. They should be implementable by persons with basic ecological training, providing reproducible results with low sampling variability. Also, they should have been used successfully in long-term monitoring programs by several different investigators or agencies.

A summary of how some candidate indicators for inland surface waters were judged against the EMAP indicator selection criteria is listed in Table 4-2. Developing a strategy for measuring indicators of inland surface water condition is greatly aided by (1) knowledge of historical distributions of fish species in many regions (Lee et al. 1980), (2) information from more than 20 years of benthic macroinvertebrate and trophic state monitoring by state agencies, and (3) the presence of minimally impacted reference areas in most regions. The EMAP-Inland Surface Waters strategy focuses on response indicators that are assemblages of organisms, as explained by Courtemanch et al. (1989), Karr (1981), Karr et al. (1986), Ohio EPA (1988), Plafkin et al. (1989), Schaeffer et al. (1988), and Schindler (1987). The data will be analyzed through use of multiple structural and functional guilds and integrating indices. Multimetric indices can be broken into separate metrics (and scores) to diagnose possible reasons for subnominal condition and better interpret biological responses.

Candidate indicators for inland surface waters that have been evaluated and proposed as research indicators are shown in Figure 4-1. The identification of high-priority research indicators for inland surface waters (Figure 4-1), although necessarily subjective, was based on our review of the literature and experience with inland surface water monitoring programs. Uncertainty remains about some research indicators because measurement techniques have not been thoroughly standardized or tested, or some question exists about whether they are sufficiently sensitive or applicable to all inland surface water classes and conditions. In some instances we have selected an analytical tool (e.g., Index of Biotic Integrity for streams of the Mississippi basin), whereas in others we only list an assemblage (diatoms and fish in lakes) because the metrics are not

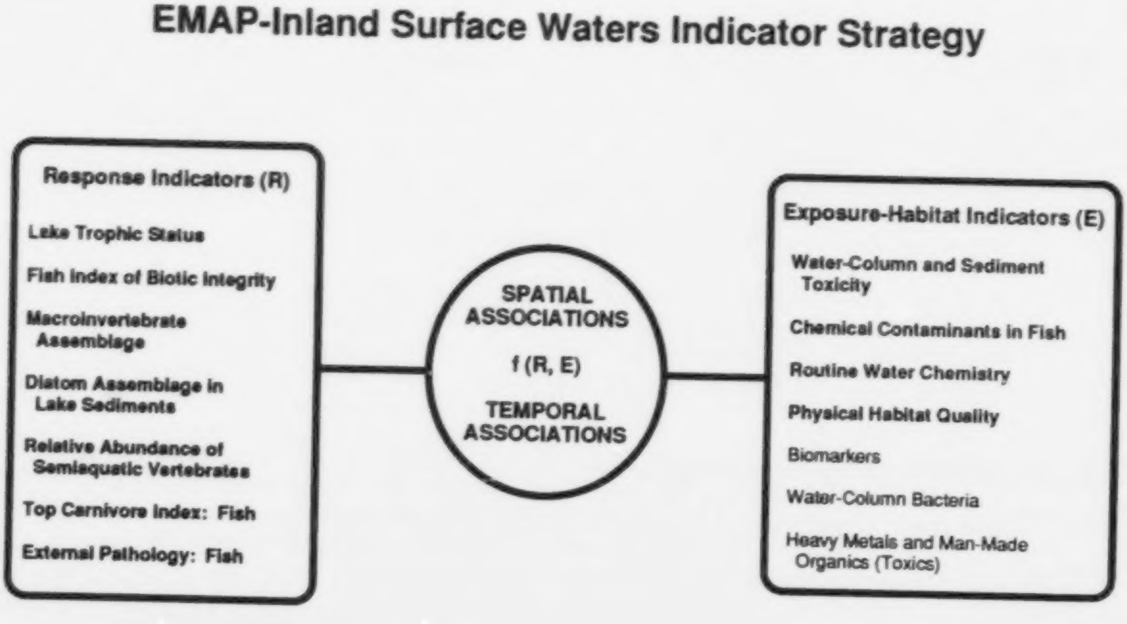
EMAP-Inland Surface Waters Indicator Strategy
Response Indicators (R)
Lake Trophic Status
Fish Index of Biotic Integrity
Macroinvertebrate Assemblage
Diatom Assemblage in Lake Sediments
Relative Abundance of Semiaquatic Vertebrates
Top Carnivore Index: Fish
External Pathology: Fish
SPATIAL ASSOCIATIONS
f (R, E)
TEMPORAL ASSOCIATIONS
Exposure-Habitat Indicators (E)
Water-Column and Sediment Toxicity
Chemical Contaminants in Fish
Routine Water Chemistry
Physical Habitat Quality
Biomarkers
Water-Column Bacteria
Heavy Metals and Man-Made Organics (Toxics)

Figure 4-1. Diagram of the proposed EMAP-Inland Surface Waters Indicator Strategy. Indicators in bold are high-priority indicators.

Table 4-1. Chronology of EMAP Indicator Development for Inland Surface Waters

Biological Monitoring for Acidification Effects Workshop (Burlington, ON), March 1988.

Indicator Workshop (Chicago, IL), October 1988

Workshop on Recovery of Lotic Communities and Ecosystems Following Disturbance: Theory and Application (Duluth, MN), October 1988

EPA Ecological Assessment Workshop (Annapolis, MD), November-December 1988

Meetings with USGS and USFWS, (Washington, DC), December 1988, March 1989, August 1989, December 1989, April 1990

Monthly Aquatic Indicator Task Group Conference Calls, January-June 1989

Biological Criteria Workshop (Annapolis, MD), February 1989

Water Quality Standards for the 21st Century (Dallas, TX), March 1989

Biological Monitoring Workshop (Athens, GA), March 1989

Rapid Bioassessment Protocols for Use in Streams and Rivers (published May 1989)

International Symposium on the Design of Water Quality Information Systems (Ft. Collins, CO), June 1989

Indicator Workshop (Corvallis, OR), July 1989

Workshop on Use of Biological Surveys for Diagnosing Aquatic Ecosystem Stressors (Minneapolis, MN), September 1989

National Symposium on Water Quality Assessment (Ft. Collins, CO), October 1989

SETAC (Society of Environmental Toxicology and Chemistry), Special Symposium on Community Metrics (Toronto, ON), October 1989

EMAP-Inland Surface Waters Workshop (Las Vegas, NV), January 1990

U.S.D.A. Forest Service Biodiversity Workshop (Corvallis, OR), February 1990

Biological Criteria Workshop (Corvallis, OR), March 1990

EPA Science Advisory Board Ecoregion/Biocriteria Research Review (Corvallis, OR), April 1990

Third Annual Ecological Quality Assurance Workshop (Burlington, ON), April 1990

ASTM (American Society for Testing and Materials) Aquatic Toxicology Symposium and Sediment Toxicity Taskgroup Meeting (San Francisco, CA), April 1990.

Biomonitoring/Biocriteria Workshop (Montgomery, AL), May 1990

Lake Indicators Workshop (New Orleans, LA), May 1990

Table 4-2. Evaluation of Some Candidate Indicators for Inland Surface Waters by EMAP Selection Criteria (H = High, M = Medium, L = Low)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	Cost Effective[12]
Selected as Research Indicators												
Lake Trophic Status	L	H	M	H	M	M	H	M	H	H	H	H
Fish IBI	H	M	H	H	H	H	H	M	M	H	M	H
Top Carnivore Index: Fish	H	M	M	H	H	M	H	M	M	H	M	H
Macroinvertebrate Assemblage	H	H	M	H	H	H	H	M	M	M	M	M
Sedimentary Diatom Assemblage	H	M	H	H	H	H	H	H	H	H	M	H
Semiaquatic Vertebrates	L	L	H	H	H	H	L	H	H	L	M	H
External Pathology: Fish	L	H	L	M	H	L	M	M	H	H	L	H
Water Column/ Sed. Toxicity	L	L	L	H	H	L	M	L	H	L	L	L
Chemical Contam: Fish	L	L	L	H	H	L	H	L	H	H	M	L
Physical Habitat Quality	H	H	H	M	H	H	H	H	M	M	L	H
Routine Water Chemistry	M	M	L	M	L	H	M	M	H	M	H	M
Biomarkers	L	H	L	M	L	L	H	H	M	M	L	L
Water-Column Bacteria	L	L	L	H	L	L	H	M	H	L	L	L
Man-Made Organics/Heavy Metals	L	L	L	M	H	L	M	L	H	L	L	L
Considered but not Selected												
Phytoplankton	L	M	L	M	L	H	H	H	H	L	L	L
Zooplankton	L	M	L	M	L	H	H	M	H	L	L	L
Growth Rate	L	H	L	L	L	L	L	M	H	L	L	L
Primary Production	L	H	L	L	L	L	L	M	H	L	L	L
Community Resp.	L	H	L	L	L	L	L	M	H	L	L	L
Nutrient Cycling	L	H	L	L	L	L	L	M	L	L	L	L

1 Correlates with changes in processes or other unmeasured ecosystem components.
2 Is applicable on a regional basis.
3 Integrates effects over time and space.
4 Relates unambiguously and monotonically to an environmental value or a relevant exposure or habitat variable.
5 Can be quantified by synoptic monitoring or by automated monitoring in a cost-effective manner.
6 Is important to overall ecological structure and function.
7 Responds to stressors or management strategies.
8 Is anticipatory by providing an early warning to widespread changes.
9 Has a standard method of measurement.
10 Exhibits low measurement error.
11 Has a historical data base or can be generated from accessible data sources.
12 Is cost effective (has low-cost and high information value).

Table 4-2. Evaluation of Some Candidate Indicators for Inland Surface Waters by EMAP Selection Criteria (H = High, M = Medium, L = Low)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	**Cost Effective**[12]
Selected as Research Indicators												
Lake Trophic Status	L	H	M	H	M	M	H	M	H	H	H	H
Fish IBI	H	M	H	H	H	H	H	M	M	H	M	H
Top Carnivore Index: Fish	H	M	M	H	H	M	H	M	M	H	M	H
Macroinvertebrate Assemblage	H	H	M	H	H	H	H	M	M	M	M	M
Sedimentary Diatom Assemblage	H	M	H	H	H	H	H	H	H	H	M	H
Semiaquatic Vertebrates	L	L	H	H	H	H	L	H	H	L	M	H
External Pathology: Fish	L	H	L	M	H	L	M	M	H	H	L	H
Water Column/ Sed. Toxicity	L	L	L	H	H	L	M	L	H	L	L	L
Chemical Contam: Fish	L	L	L	H	H	L	H	L	H	H	M	L
Physical Habitat Quality	H	H	H	M	H	H	H	H	M	M	L	H
Routine Water Chemistry	M	M	L	M	L	H	M	M	H	M	H	M
Biomarkers	L	H	L	M	L	L	H	H	M	M	L	L
Water Column Bacteria	L	L	L	H	L	L	H	M	H	L	L	L
Man-Made Organics/Heavy Metals	L	L	L	M	H	L	M	L	H	L	L	L
Considered but not Selected												
Phytoplankton	L	M	L	M	L	H	H	H	H	L	L	L
Zooplankton	L	M	L	M	L	H	H	M	H	L	L	L
Growth Rate	L	H	L	L	L	L	L	M	H	L	L	L
Primary Production	L	H	L	L	L	L	L	M	H	L	L	L
Community Resp.	L	H	L	L	L	L	L	M	H	L	L	L
Nutrient Cycling	L	H	L	L	L	L	L	M	L	L	L	L

1 Correlates with changes in processes or other unmeasured ecosystem components.
2 Is applicable on a regional basis.
3 Integrates effects over time and space.
4 Relates unambiguously and monotonically to an environmental value or a relevant exposure or habitat variable.
5 Can be quantified by synoptic monitoring or by automated monitoring in a cost effective manner.
6 Is important to overall ecological structure and function.
7 Responds to stressors or management strategies.
8 Is anticipatory by providing an early warning to widespread changes.
9 Has a standard method of measurement.
10 Exhibits low measurement error.
11 Has a historical data base or can be generated from accessible data sources.
12 Is cost effective (has low-cost and high information value).

yet integrated into an index. Comparison of responses from a number of response indicators to known stressors is necessary to reveal whether these research indicators are appropriate and sensitive for determining status and trends in ecological condition.

A brief description of each research indicator is given here. More detailed descriptions of the indicators, their application, suitable index period, variability, and research needs are listed in Appendices B and C, as referenced by the code in parentheses at the end of each description below.

4.2.4.1 *Response Indicators for Inland Surface Waters*

Response indicators are used by EMAP to quantify and classify the condition of ecological resource classes. Eight response indicators have been selected as research indicators for inland surface waters, all of which are recognized as having high-priority status.

Lake trophic status. Is sensitive to chemical stressors, particularly nutrients. It relates to lake primary production and clarity and is of great concern to fishermen, boaters, and swimmers. (B.1)

Fish Index of Biotic Integrity. Is sensitive to physical, chemical, and biological stressors; assesses taxonomic and trophic groups, sensitive and tolerant species, and community abundance and condition; integrates species composition data into an index understandable by the general public and meaningful to ecologists. (B.2)

Macroinvertebrate assemblage. Is used in the same way as the fish IBI and complements it; this indicator is necessary in small streams containing few fish species or where fish are absent. (B.3)

Diatom assemblage in lake sediments. Diatoms are sensitive to water quality and substrate changes; this indicator integrates water and bottom conditions and can be used to assess food base and aesthetic appearance of lakes. Existing data bases make it useful for assessing historical change. (B.4)

Relative abundance of semiaquatic vertebrates. Is sensitive to physical, chemical, and biological stressors; along with top carnivores, often the first species to disappear; of great interest to the public. It could include amphibians, reptiles, birds, and mammals. (B.5)

Top carnivore index: Fish. Top carnivores are sensitive to harvest pressure and physical and chemical habitat deterioration; the index is most useful for salmonid streams containing only one or two fish species; it can be used to assess condition of species of greatest interest to the public. The index includes information on size classes, growth, abundance, anomalies, and management actions such as stocking and catch restrictions. (B.6)

External pathology: Fish. Is sensitive to general stress and toxic chemicals; it can be used to assess presence of disease and condition of populations and is of considerable interest to persons who eat fish. (B.7)

4.2.4.2 *Exposure and Habitat Indicators for Inland Surface Waters*

Exposure and habitat indicators are used by EMAP to identify and quantify changes in exposure and physical habitat that are associated with changes in response response indicators and to address the traditional concerns of management agencies and the public. Seven exposure and habitat indicators have been selected as research indicators for inland surface waters, four of which are recognized as having high-priority status.

High-Priority Research Indicators

Water-column and sediment toxicity. Provides a snapshot evaluation of toxicity using bioassays; can be used to estimate the severity of toxic conditions nationwide and identify "hot spots." (B.8)

Chemical contaminants in fish. Assesses bioconcentration and potential ecological hazard to long-lived and large species; direct measure of potential health problems by human consumption. (B.9)

Routine water chemistry. Evaluates a number of conventional chemicals of importance to aquatic life; some chemicals are used to calculate trophic state; assesses eutrophication, acidification, and salinity. (B.10)

Physical habitat quality. Is sensitive to hydrological and physical changes; integrates morphological condition of stream or lake bed and banks; assesses suitability for spawning, rearing, and feeding by biota; offers a measure of the aesthetic appearance of the water body. (B.11)

Other Research Indicators

Biomarkers. A desirable feature of a monitoring program would be to detect an organism's response to human-induced stresses at the biochemical and cellular level before the stresses produce a detectable response at the organism and population levels. Although the use of biomarkers as early-warning response indicators requires more basic research, their present value for regional survey monitoring is to provide information to support or refute hypotheses on why ecological condition of inland surface waters is subnominal. (G2.1-G2.11)

Water-column bacteria. Provides a snapshot evaluation of bacterial contamination; can be used to gauge the swimmability of waters and the risk of illness from consumption of fish or shellfish. (B.12)

Heavy metals and man-made organics (toxics). Concentrations of toxics in waters and sediments are useful for evaluating possible acute and chronic exposures to aquatic biota. Application of these indicators is recommended for sites with known or suspected toxicity. (B.13)

4.2.4.3 *Stressor Indicators for Inland Surface Waters*

Stressor indicators of importance to inland surface waters differ from those important to other resource categories. Assessments of proportions of terrestrial vegetation and diversity, patch size and connectivity, key physical features, and criteria air pollutants are markedly less important for inland surface waters than are the landscape loading stressors (proportions of land use, pollution sources, drainage modifications). Further, our concern is at the watershed and drainage level, not at the landscape sampling unit (LSU) level. Additional research is required to determine if regional correlations between landscape features and inland surface water condition can result from randomly located LSUs as opposed to the more traditional watershed inventory approach. More detailed discussions of EMAP stressor indicators are presented in Sections 9.5 and 10.

4.2.5 Inland Surface Water Indicators Not Appropriate for EMAP

Community process and rate measures (primary production, respiration, nutrient cycling) are important measurements of ecological condition in surface waters. Long-term data indicate, however, that they show little change before, or upon the occurrence of, important structural changes, presumably because there are too many compensating mechanisms (Schaeffer et al. 1988, Schindler 1987). Important process changes are often difficult to detect because the background variability is high (i.e., the signal-to-noise ratio is low). Use of these measures also requires multiple measurements and site visits, which are incompatible with EMAP's index period concept and spatial design (see Section 2.2).

Our focus on community structure, rather than on population rates, precludes estimating population birth, growth, or mortality rates. These rates tend to be more variable than community measurements and to require frequent sampling for meaningful assessments. We do, however, propose to include population structure measurements (density, size classes, condition, and scale annuli for growth estimation) of top carnivores or key species in species-depauperate systems.

Aside from sediment core diatoms and pigment concentration (in the trophic state index), we would not recommend assessing microorganisms or plankton as response indicators. Relative to macroorganisms, such groups have poorly developed taxonomies, and taxon abundances fluctuate dramatically over short time periods. Pathogenic bacterial density is included as an exposure indicator.

Internal gross pathology of fish is too time-consuming for regional surveys. External pathology is an appropriate substitute, however, and is associated with desirability of game fish. Exposure and habitat indicators should be designed to evaluate "presence of" and "absence of" conditions in a reasonably efficient manner. We recommend focusing on physical habitat quality and biological measurements of toxicity or stress, instead of measurements of toxic chemical concentrations. The latter are extremely expensive, often relate poorly to toxicity, and involve a potentially enormous number of chemicals, many of which lack toxicity criteria. Limited sampling for toxics would be possible in special cases (e.g., a repeat of the national dioxin survey).

4.3 APPLICATION OF INLAND SURFACE WATER INDICATORS

All inland surface water resources are impacted to some degree and thus could be considered subnominal in the strictest sense, or, if we consider human impacts natural, all the resources are nominal. Some compromise between these two extremes is needed to set criteria, one that is useful and protective without being arbitrary. Several methods (involving the use of regional reference sites, historical data, pristine sites, and models) for determining numerical criteria can be used to decide if ecological condition, as determined by values of response indicators, is nominal or subnominal. Each has advantages and disadvantages.

Our preferred option for interpreting regional or national condition of inland surface waters uses a series of regional reference sites (Hughes et al. 1986; Hughes 1989). The use of reference sites integrates professional judgement, an understanding of historical or pristine conditions, and knowledge of current ecological research in selecting the least disturbed but typical sites within a region. The condition (response indicator values) and statistical variability found in the reference sites become the model for the region. This approach is being considered by the EPA in its bioassessment, biocriteria, and nonpoint-source programs (Plafkin et al. 1989; U.S. EPA 1988; 1989a,b). The regional reference site approach, however, may require sampling as many as 800 benchmark sites (50 sites each for 16 surface water classes) in the conterminous United States. Site selection would require careful analyses of mapped data and conscientious reconnaissance of candidate sites. Although large rivers or large lakes are not planned for inclusion in the initial phases of implementation, reference sites for these resource classes can be selected simply by determining minimally impacted reaches or shorelines in various sections of the river or lake (Hughes and Gammon 1987; Ohio EPA 1988; these references also describe sampling methods for such waters).

Under ideal conditions, we could compare EMAP sample data with historical data (the second option) or with data from existing pristine sites (the third option). These approaches are apparently what the authors of P.L. 92-500 had in mind for the phrase "physical, chemical, and biological integrity" (National Commission on Water Quality 1976). Unfortunately, historical data of appropriate quality are rare, except for sedimentary diatoms. Existing pristine sites could be used in place of historical data, but these sites are often protected because they are unusual and thus are rarely regionally representative. Additionally, given the extent of atmospheric deposition, few sites can be considered truly pristine.

A fourth option for determining inland surface water condition is through the use of one or more models. Models may be based on field data for a key variable or set of variables, complex ecosystem studies, trophic state models, or laboratory toxicity tests; however, key exposure variables differ considerably across the nation. Current research on stream ecosystems, for example, stresses physical habitat in the Pacific Northwest, flow in the Intermountain West, and sediment in the Midwest. Adequate research to represent this diversity of exposures requires many models and much data collection. Ecosystem studies are an extremely expensive way to generate models, and the sites studied are likely to be representative of few resource classes. Trophic state models are inappropriate for streams and incorporate little insight into stressors other than the oversupply of nutrients. Toxicity tests have little relevance for nontoxic stressors (e.g., physical habitat, flow, food base, biotic management, nontoxic contaminants).

Given the proposed set of research indicators, how are they linked, what measurements are to be taken, and how are the data to be analyzed and integrated? These linkages and potential scoring criteria are outlined for response indicators in Table 4-3 and for exposure and habitat indicators in Table 4-4.

4.4 RESEARCH NEEDS FOR EMAP-INLAND SURFACE WATERS

We have outlined a series of options for determining subnominal thresholds for the response indicators. While we are likely to adopt the use of regional reference sites for setting these thresholds, this subject would benefit from substantial research. Reference site selection and sampling would be required before indicators are monitored within a region. Because the concept of reference sites is also central to biological criteria for surface waters (U.S. EPA 1990), EMAP may further serve EPA and the states by selecting and monitoring a set of regional reference sites.

The suite of research indicators for inland surface waters requires diverse plans for their future development. In the near term, the selected fish and macroinvertebrate indices require development and testing outside the regions and water bodies in which they initially have been developed (e.g., Miller et al. 1988 for the IBI). For example, how applicable is the IBI to the reservoirs of the southeastern United States? What macroinvertebrate guilds dominate sand-bottomed desert and plains streams? We also must develop and assess a diatom assemblage index or expand the environment reconstruction approach outlined by Battarbee (1986). Three general areas for long-term indicator development are ecological guilds, exposure indicators, and monitoring as research.

4.4.1 Ecological Guilds

The fish and macroinvertebrate indices are based on a limited number of metrics. Development of several other metrics would offer further insight into ecological assessments. For example, Margalef (1963) listed several characteristics of mature and immature ecosystems from which additional indicator guilds could be developed. How might other guilds and the guilds we have already proposed as research indicators respond to different types and intensities of disturbance?

We need answers to questions regarding "natural" and acceptable variability versus "anthropogenic" and unacceptable variability. There is evidence that some perturbation is stimulatory. Are communities/species that experience considerable natural variability more resilient (pre-adapted) to disturbance? Does variability consistently increase with disturbance? If the answer to both of these questions is yes, then perhaps some statistical measurement of species variability itself would be a useful indicator. How is variability that results from natural changes distinguished from variability resulting from anthropogenic changes, especially in a setting where historical anthropogenic changes now appear "natural." Examples include absence of snags in rivers,

Table 4-3. Linkages Between Potential Environmental Values (Assessment Endpoints), Measurements, Metrics, and Response Indicators for EMAP Inland Surface Waters

Environmental Values (Assessment Endpoints)	Measurements	Metrics	Indicators (with scoring criteria)		
Number or % of Fishable Waters			**Fishability Index (0 or 1)**		
gamefish sp. present	species identification	relative abundance	Absent (0)		
gamefish abundance	number of individuals	catch per unit effort (CPUE)	<0.002 [1/8H] (0)		
gamefish size	individual length/weight	% keepers, % trophy	<50% keepers (0)		
fish appearance	external anomalies	% anomalies	>1% with anomalies (0)		
fish edibility	toxic concentrations	consumption criteria violations	restricted >once/year (0)		
fishery sustainability	individual weight, length, scales; stocking records, catch restrictions	age/size structure % wildfish, % keepers	juveniles absent (0) adults stunted (0) <50% wildfish (0) <50% keepers (0)		
Trophic Condition					
noxious algal blooms, surface scums	pigment concentrations, visual, sediment diatom sp. & abundance	% blue-green algae % nuisance species	>10% (0) >10% (0)		
macrophytes	macrophytes	% of lake macrophyte dominated	>25% littoral zone (0)		
low transparency	Secchi depth	Secchi depth	<2 m (0)		
noxious taste/odor	threshold odor	threshold odor number (TON)	TON > 10 (0)		
fish kills	hypolimnion oxygen concentrations	% depth <3 mg DO/l	>50% (0)		
trophic state	pigment concentrations; total phosphorus; Secchi depth; total nitrogen	trophic state index (TSI)	**Trophic State Index** (< 30, 30-60, > 60		
change in trophic state	sediment diatom sp. & abundance	% oligo/meso/eu/dystrophic sp.; dominant sp.; % epiphytic; % planktonic	rate of historical trophic state change (▲ TSI/YR)		
Biological Integrity			**Biointegrity Index**[1]		
			(1)	(3)	(5)
"dead" lakes/streams	no. of individuals[2]	CPUE	<33%	33-67%	>67%[3]
declines in species richness	sp. identification and number[2]	no. of species	*	*	*
declines in sensitive species	sp. identification and number[2]	% sensitive	*	*	*
increases in tolerant species	sp. identification and number[2]	% tolerant	>25	10-25	<10
increases in exotic species	sp. identification and number[2]	% exotic	>10	1-9	<1
reproductive failure/population sustainability	- individual length & weight (fish) --number of individuals (birds)	age/size structure CPUE	>1+ See CPUE above	1+->1+(3)	0+->3+
evidence of kills	questionnaire	kill frequency	1-5 yr	>5 yr	no kill
increased anomalies	external anomalies (fish)	% anomalies	>5	1-5	<1
decreased abundance	number of individuals[2]	CPUE	See CPUE above		
decreased maximum individual size	individual length & weight (fish)	% old growth	<1	1-9	>10
historical dislocation	species & abundances (diatoms)	% similarity	<25	25-75	>75

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[1] The Index of Biotic Integrity (IBI) and the Biotic Condition Index (BCI) will be used for stream fish and macroinvertebrate assemblages; criteria for both are based largely on regional reference site values.

[2] Includes sedimentary diatoms, fish, and birds for lakes; macroinvertebrates, fish, and birds for streams.

[3] Determined from regional reference site values.

Table 4-4. Linkages Between Potential Environmental Values (Assessment Endpoints), Measurements, and Exposure Indicators for EMAP Inland Surface Waters

Environmental Values (Assessment Endpoints)	Measurements	Indicators
Are fish safe to eat?	concentrations of muscle toxics (metals, organics)	violation of consumption criteria >1/year
Are waters becoming more eutrophic?	P, N, Ca, Cl, TSS, Secchi, temp., pigments, lake sedimentary diatom spp. & abundance	Trophic State Index (TSI) % eutrophic, mesotrophic, oligotrophic
Are waters becoming more saline?	Cl, TDS lake sedimentary diatom sp. & abundance	total chloride, total dissolved solids % halophilic, halophobic
Is water acidity changing?	pH, DIC, ANC, Al, SO_4, NO_3, Cl, DOC TN, Na, K, Mg, Ca, NH_4 lake sedimentary diatom sp. & abundance	ANC, anions, cations
Are waters warming?	% canopy (streams)	% canopy (< 25, 25-50, 51-75, >75) % sternothermal, metathermal, eurythermal
Are waters becoming more turbid?	Secchi, turbidity, TSS	Secchi depth, turbidity, total suspended solids
Are sediments toxic to aquatic life?	*Hyalella, Ceriodaphnia & Pimephales* mortality & reproduction or growth	toxicity significantly greater than controls
What is the critical level of habitat alteration for eliminating habitat-sensitive fish & wildlife?	LAKES: % littoral dominance, temp. & DO profiles, lake area, max. depth, level fluctuation, substrate, cover, depth variation, shoreline development, land use, and vegetation.	Lake Habitat Quality Index (LHQI)
To what degree is biological impairment due to natural habitat conditions?	STREAMS: Widths, depths, substrate, cover, embeddedness, flow, channel alteration/complexity, pool/riffle/run/bend, bank stability, riparian vegetation, immediate land use.	Stream Habitat Quality Index (SHQI) (% regional reference site value < 25, 26-50, 51-75, >75)

loss of headwater streams and wetlands, and altered trophic states. Might highly stressed systems be more structurally stable than natural or slightly stressed systems if only the most tolerant organisms persist there? Perhaps variability as a function of stress is described by a hyperbolic function.

To what degree are species that are tolerant of naturally occurring stressors also tolerant of anthropogenic contaminants? Species differ in their life cycles (simple-complex), reproduction (r-K), survivorship (type 1, 2, or 3), feeding and habitat requirements (specialized-generalized), life span (short-long), and individual size at maturity (small-large). Are any of these species characteristics effective measures of perturbation in surface waters? Thoughtful examination of the behavior of various guilds is certain to increase our understanding of ecological guilds and their response to different stressors.

4.4.2 Exposure and Habitat Indicators

Several aspects of exposure and habitat indicators require development. Biomarkers appear to present some promising possibilities for application in EMAP; however, additional research is needed to improve our ability to interpret the results from these measurements. Given the increasing range of chemicals being introduced into aquatic systems, there is a growing need for measurement techniques that provide a chemical screen for various classes of compounds. These screens would improve our ability to identify potential exposure to classes of chemical compounds and improve the diagnostic capability of EMAP and other programs that use bioassessment.

4.4.3 Monitoring as Research

Careful study of the data base generated by EMAP is likely to produce long-term improvements in our understanding and application of ecological indicators. A consistently collected set of species composition and abundance data from across the nation can be used to produce unequivocal answers about the various components of indicator variability (measurement, index period, interannual, among-site, within-site). Presently, our variability estimates are based on a few sites in a small number of places over relatively short time frames.

It is useful to consider our current environmental management practices as manipulations or experiments in progress; however, few scientists are proposing hypotheses or collecting sufficient data to test them. EMAP offers scientists that opportunity because the data will be freely available. Comparisons of disturbed and relatively undisturbed sites would reveal the ecological impairments, on a national and regional scale, of our current land use practices and water resource regulations. These observations can serve to generate additional hypotheses and bona fide experimental manipulations, especially ecosystem restorations. Research on restoration ecology in streams and lakes would not only improve our knowledge of indicators, it would also demonstrate the ecological benefits of restoration on a national scale.

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SECTION 5

INDICATOR STRATEGY FOR WETLANDS

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5.1 INTRODUCTION

Wetlands are "areas that are inundated or saturated by surface or ground water at a frequency or duration to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions" (33 CFR Section 328.3). Wetlands are productive, diverse ecosystems that are important to both the environmental and economic health of the nation, and wetlands provide habitat for wildlife and endangered species, nurture commercial and recreational fisheries, help reduce flood damages, and abate water pollution (Conservation Foundation 1988). Although the EMAP wetland resource category includes all wetlands as defined above, this section focuses on inland wetlands.

5.1.1 Legislative Mandate for Wetlands Monitoring

Historically, wetlands have been the object of efforts to convert land to "more productive" use. Such efforts have resulted in the loss of more than 50% of the nation's contiguous wetlands since presettlement times. Wetlands are currently affected by both habitat modification (including both hydrologic and physical alteration) and contamination from point and nonpoint sources of pollution.

As perceptions of the role of wetlands in the landscape have changed, pressure has mounted to conserve these resources for future generations. Since the early 1970s, interest in wetland protection has increased significantly as scientists begin to identify and quantify the many values of these ecosystems. Interest in wetland protection has been translated at both the federal and state level into laws and public policies (Mitsch and Gosselink 1986). Table 5-1 lists the most pertinent legislation protecting wetland function and extent. The most recent additions to this list include the proposed EPA-Army Corps of Engineers wetland mitigation policy and the National Wetland Forum's recommendations of "no net loss of the nation's remaining wetland base, as defined by acreage and function" (Conservation Foundation 1988).

Despite current progress in wetlands conservation, there is concern that the successes in preserving wetland acreage fall far short of what is needed to effectively maintain wetland functions (Zelazny and Feierabend 1988). Implementation of EMAP will allow progress in protecting the wetland resource to be evaluated at both regional and national scales.

5.1.2 Wetland Resource Classification

The proposed resource classes for inland wetlands are listed in Table 5-2. These classes were modeled on the Cowardin wetland classification system (Table 5-3, Cowardin et al. 1979), but minor modifications were made to meet EMAP monitoring objectives and its design constraints. The EMAP sampling design constraints are to (1) ensure that the wetland classification includes classes that are functionally distinct; (2) limit the number of wetland classes per region to enable an adequate number of samples per class, given logistics and costs; (3) include only those wetland classes that would be detectable on 1:40,000 aerial imagery (resource sampling units greater than 1.0 ha on average); and (4) define distinct and logical boundaries between

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Table 5-1. Major Federal Laws, Directives, and Regulations for the Management and Protection of Wetlands

Directive	Date	Responsible Agency
Executive Order 11990 Protection of Wetlands	May 1977	All agencies
Executive Order 11988 Floodplain Management	May 1977	All agencies
Federal Water Pollution Control Act (PL 92-500) as Amended	1972, 1977	
Section 404--Dredge and Fill Permit Program		All agencies
Section 401--Water Quality Certification		All agencies
National Environmental Policy Act	1975	All agencies
Coastal Zone Management Act	1972	Office of Coastal Zone Management

Table 5-2. Proposed EMAP-Wetland Resource Classes

System	Class	Colloquial Name
Lacustrine	Shallows	Aquatic beds, mudflats
	Emergent (flooded)	Marsh
Palustrine	Shallows	Aquatic beds, mudflats, open water, playa lakes or basins, farm ponds, prairie pothole
	Emergent	
	Flooded	Marsh, prairie pothole
	Saturated	Fen, bog, wet meadow
	Scrub/Shrub	
	Saturated	Carolina bays, pocosins, bog
	Flooded	Carr
	Forested	
	Saturated	Blue spruce bogs, white cedar swamps
	Flooded	Bottomland hardwoods, cypress swamps
Riverine	Shallows	Aquatic beds, mudflats
	Emergent (flooded)	Marsh

Table 5-3. Traditional Cowardin System for Defining Wetland Classes[1]

System	Subsystem	Class
Lacustrine	Littoral	Aquatic Bed Unconsolidated Shore Non-Persistent Emergent
Palustrine		Aquatic Bed Unconsolidated Shore Moss-Lichen Emergent Scrub-Shrub Forests
Riverine	Lower Perennial	Aquatic Bed Unconsolidated Shore Non-Persistent Emergent

[1] From Cowardin et al. (1979).

wetland resource classes and the classes selected by the EMAP Inland Surface Waters and Near-Coastal groups.

We adopted the general framework of the Cowardin wetland classification scheme (including the Lacustrine, Palustrine, and Riverine systems), but modified the classes according to the following rules:

- Lumping of many subclasses of the full Cowardin et al. (1979) wetland classification was deemed necessary to allow for an adequate number of samples for each class that was refined, given the current EMAP sampling design (Section 2.2). For example, aquatic beds, mudflats, and open water areas are lumped into a new class termed Shallows.

- A vernal pools class was not included because the pools would not be detectable by the highest resolution imagery currently planned to be provided by EMAP landscape characterization activities (1:40,000 scale with 1.0-ha minimum area).

The colloquial names of the wetlands in each class were included for clarification. These were derived from (a) the list of colloquial wetland classes provided by the EPA Office of Wetlands Protection and (b) both regional and local sources of wetland classifications (often provided by regional wetland experts). This wetland class list will be refined in cooperation with the EPA Office of Wetlands Protection and the U.S. Fish and Wildlife Service's National Wetland Inventory (NWI).

Given the legislative mandate for wetland monitoring and a classification system to emphasize ecologically important regional wetland resources, the following four topics of the EMAP indicator strategy for wetlands are discussed in this section.

1. Wetland qualities and health as perceived by the public and their relevance to the selection of EMAP indicators
2. High-priority research indicators that have been proposed for further testing by EMAP, utilizing both small-scale field testing and analysis of existing data sets
3. Other research indicators and research priorities that will be addressed during the next five years
4. Determination of subnominal thresholds for response indicators and the importance of understanding causal pathways of potential stressors in wetlands

5.2 IDENTIFICATION OF WETLAND INDICATORS

5.2.1 Perceptions of Wetland Condition

Depending on the U.S. region, wetlands represent 3-36% of the landscape. They offer opportunities for aesthetics and recreation (hiking, canoeing, birding, hunting, and fishing), for preservation and protection of native animal species, and for research and education. Recent national, state, and private acquisitions of wetland areas underscore the increasing public awareness of the importance of preserving wetlands.

Loss of wetland acreage has been highlighted in the minds of the public in recent years so that acreage by itself has become virtually synonymous with wetland condition. Loss of wetland acreage and declines in the quality of wetland habitat have been suggested as causes of decline in some animal species. Many species of threatened birds and mammals have been shown to be "wetland-dependent," a term that has become increasingly important to the public. However, the focus on loss of wetland acreage and its direct effects on native animal species has overshadowed a second extremely important change that may be occurring: the loss of wetland functional integrity or health. This change, which is demonstrated by rapid changes in species composition due to the invasion of exotic species and species considered noxious, is often attributed by the public to human impacts.

5.2.2 Environmental Values for Wetlands

Environmental values for wetlands are related to three groups of ecological functions: (1) water quality functions, (2) water quantity (hydrologic) functions, and (3) ecological support. In addition, "no net loss of wetlands" is now a goal for federal agencies because of the importance of these functions.

Wetlands serve two primary functions relative to water quality (Preston and Bedford 1988). They improve water quality through sedimentation, pollutant immobilization, and limited uptake of various pollutants and nutrients (Kuenzler 1989). Secondly, their organic substrate can act as a filter to immobilize substances as they pass from surface waters through wetland soils to ground waters.

The hydrologic functions associated with wetlands include water storage, flood abatement, and ground water recharge and discharge. Wetlands can act as buffers against flooding by storing large influxes of storm water and releasing it slowly, minimizing flood peaks and maintaining base flow. Wetlands can serve as either ground water discharge or infiltration areas, depending on local hydrologic and climatologic regimes. In individual wetlands, bidirectional flow is a seasonal characteristic of some wetland classes.

Wetlands are also important for supporting aquatic and terrestrial organisms. Wetland productivity, which often exceeds that of surrounding ecological communities, can sustain not only internal trophic relationships but also external trophic relationships, that is, those that depend on the export of biomass from wetlands. Wetlands also offer habitat features not found in other vegetation types.

5.2.3 Hazards to Wetlands

Four major hazards are associated with wetland loss or damage: (1) hydrologic source alteration, (2) direct physical alteration, (3) toxic contaminant influx, and (4) nutrient input and sediment imbalance. Vegetation removal, invasion by exotic or nuisance species, and global atmospheric change are also hazards. The relative importance of these hazards varies by region and according to the specific type and configuration of the hazard. Although global climate change is not presently a known stressor, it has the potential for overshadowing the effects of all other stressors in the future. Excellent overviews of hazards to wetlands are provided in Adamus (1988) and Mitsch and Gosselink (1986).

5.2.4 Wetland Indicators Appropriate for EMAP

To date, no widely accepted set of measures for determining wetland health exists, although many candidate indicators have been suggested. The approach to selecting a set of research indicators for inland wetlands is discussed below. A chronology of indicator development activities by EMAP-Wetlands scientists is outlined in Table 5-4. A written external peer review of these indicators was performed in April 1990 (Appendix I.8), followed by a review by the EPA Science Advisory Board in May 1990. EMAP workshop participants and external reviewers are listed in Appendix I.

The designation of wetland research indicators as having high-priority status, while necessarily subjective, was based on a review of the literature and experience with wetland monitoring programs. For some high-priority research indicators, either measurement techniques have not been thoroughly standardized or tested or some question exists about whether they are sufficiently sensitive or applicable to all wetland classes. Small-scale field tests and regional demonstration projects will further aid the development of standardized protocols for high-priority research indicators. Comparison of how response indicators react to known stressors is necessary to reveal whether research indicators are appropriate and correspond to the environmental values for wetlands (see 5.2.2).

A goal of EMAP is to monitor a set of response, exposure, and habitat indicators that address all the major hazards or impacts that wetlands are (or could be) experiencing. Although it is impossible to anticipate all

Table 5-4. Chronology of EMAP Indicator Development for Wetlands

1989-1990	Refined a list of candidate wetland indicators through informal interactions with wetland scientists.
August 1989	Presented an initial list of proposed EMAP indicators for wetlands.
October 1989	Presented a description of EMAP wetland indicators at the EPA Water Quality Symposium.
March 1990	Comprehensively reviewed the literature on wetland indicators and mapping found sites during the compilation of a draft report for the EPA Office of Policy and Program Evaluation.
April 1990	Review of EMAP wetland indicators by external reviewers.
May 1990	Review of EMAP wetland indicators by the EPA Science Advisory Board.

future hazards (emerging problems), the set of indicators is linked to fundamental ecological processes andthus could indicate current or impending widespread impacts. Ultimately, we need to develop the knowledge base that will allow us to distinguish those impacts that are detrimental to long-term wetland sustainability from effects of natural perturbation (e.g., climate or beaver activity) as well as resource management (e.g., waterfowl management).

In evaluating a list of candidate indicators for wetlands, research indicators were proposed that are believed to be both widely applicable and sensitive to wetland hazards (Table 5-5). The research indicators assigned high-priority status have been extensively used for characterizing or describing site-specific wetlands. Criteria used for evaluating candidate wetland indicators include those listed in Table 5-5.

The response, exposure, and habitat indicators for wetlands proposed for further testing are illustrated in Figure 5-1. A brief description of each research indicator is provided below. More detailed descriptions of these indicators, their application, suitable index period, variability, and research needs are listed in Appendices C and G, as referenced by the code in parentheses that follows each description below. More detailed discussions of EMAP stressor indicators are presented in Sections 9.5 and 10.

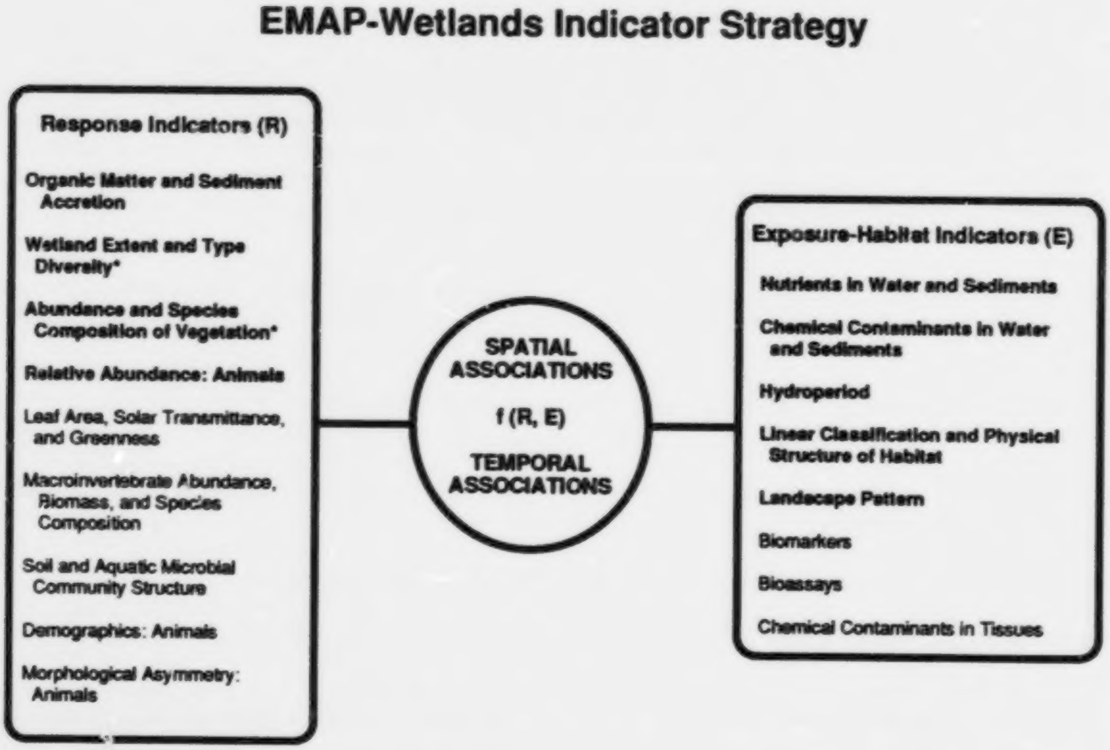
EMAP-Wetlands Indicator Strategy
Response Indicators (R)
Organic Matter and Sediment Accretion
Wetland Extent and Type Diversity*
Abundance and Species Composition of Vegetation*
Relative Abundance: Animals
Leaf Area, Solar Transmittance, and Greenness
Macroinvertebrate Abundance, Biomass, and Species Composition
Soil and Aquatic Microbial Community Structure
Demographics: Animals
Morphological Asymmetry: Animals
SPATIAL ASSOCIATIONS
f (R, E)
TEMPORAL ASSOCIATIONS
Exposure-Habitat Indicators (E)
Nutrients in Water and Sediments
Chemical Contaminants in Water and Sediments
Hydroperiod
Linear Classification and Physical Structure of Habitat
Landscape Pattern
Biomarkers
Bioassays
Chemical Contaminants in Tissues

Figure 5-1. Diagram of the proposed EMAP-Wetlands Indicator Strategy. Indicators in bold lettering are high-priority research indicators. Response indicators with an asterisk (*) also function as exposure and habitat indicators.

Table 5-5. Evaluation of Some Candidate Indicators for Wetlands by EMAP Selection Criteria (H = High, M = Medium, L = Low)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	Cost Effective[12]
Selected as Research Indicators												
Wetland Extent/Type Diversity	M	H	M	H	H	H	H	H	H	H	H	H
Organic Matter/Sediment Accretion	H	H	H	M	M	H	H	M	H	M	M	M
Abundance/Spp. Comp.: Vegetation	M	H	H	H	M	H	M	L	H	M	H	M
Water Birds	L	H	H	H	M	M	M	L	M	M	H	H
Nutrients in Water/ Sediments	M	H	L	M	H	M	M	M	H	L	M	M
Chemical Contaminants in Water/ Sediments	M	H	M	H	M	H	H	M	H	H	L	M
Hydroperiod	H	H	M	H	M	H	H	M	L	M	L-M	L
Macroinvertebrates	M	H	M	H	M	M	H	M	M	M	L-M	L
Leaf Area/ Transmittance/ Greenness	H	H	M	M	M	H	M	L	M	M	M	M
Soil and Aquatic Microbes	H	H	L	L	L	H	H	M	H	L	L	L
Chemical Contaminants in Tissues	H	H	H	H	M	M	M	M	M	M	L	L
Bioassays	M	H	L	M	L	L	M	M	M	L	L	L
Considered but Not Selected												
Biomass	H	H	M	L	M	M	L	L	H	L	L	L
Primary Production	H	H	M	L	L	H	L	L	H	L	L	L
Nutrient Cycling	H	H	L	M	L	H	L	L	L	L	L	L
R[illegible]sion	M	L	M	L	L	H	L	L	L	L	L	L
[illegible]cition	H	H	M	L	L	H	L	M	H	L	L	M
Fish Community Structure	M	M	M	L	M	M	M		M	L	L	M

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1 Correlates with changes in processes or other unmeasured ecosystem components.
2 Is applicable on a regional basis.
3 Integrates effects over time and space.
4 Relates unambiguously and monotonically to an environmental value or a relevant exposure or habitat variable.
5 Can be quantified by synoptic monitoring or by automated monitoring in a cost-effective manner.
6 Is important to overall ecological structure and function.
7 Responds to stressors or management strategies.
8 Is anticipatory by providing an early warning to widespread changes.
9 Has a standard method of measurement.
10 Exhibits low measurement error.
11 Has a historical data base or can be generated from accessible data sources.
12 Is cost-effective (has low cost and high information value).

5.2.4.1 *Response Indicators for Wetlands*

Response indicators are used by EMAP to quantify and classify the condition of ecological resource classes. Nine response indicators have been selected as research indicators for wetlands, four of which are recognized as having high-priority status.

High-Priority Research Indicators

Organic Matter and Sediment Accretion. Sediment accretion refers to the accumulation of both mineral and organic matter in wetlands. The mineral portion of sediments, in particular, enters the system through external pathways (such as overbank flow) and is thus a surrogate for wetland hydrology. Sediment accretion rates also provide a good indication of trends in trophic status and long-term sustainability of ecological values. Changes in environmental processes on surrounding landscape, such as accelerated rates of drainage or erosion, are often reflected in altered wetland hydrology and subsequent sediment accretion rates. The rates of organic matter and sediment accretion integrate both the (1) hydrologic history and (2) vegetation response and primary productivity of a wetland. The rates of organic matter and sediment accretion may indicate water purification capacity, habitat quality for particular groups of species, and the long-term sustainability of a wetland. Significant change in these rates often is an early warning of deteriorating wetland condition. (C.1)

Wetland Extent and Type Diversity. This measurement indicates the geographic extent and distribution of wetlands. Changes in areal extent and diversity of vegetation types indicate regional or national "hot spots" of detrimental impacts. (C.2)

Abundance, Diversity, and Species Composition of Vegetation. Wetland plants are reliable indicators of certain stressors, hydrologic conditions, and habitat values. Plants are immobile and sampling methods are well developed. (C.3)

Relative Abundance: Animals. Presence of certain water bird species is indicative of landscape health. Water birds also serve as bioaccumulators and are highly noticeable to the public. Contamination or population measures may reflect problems with other resource categories that serve as part-time habitat. (C.4) The usefulness of other classes of animals as indicators of wetland health is being evaluated. (G1.1)

Other Research Indicators

Leaf Area, Solar Transmittance, and Greenness. Changes in canopy characteristics (e.g., premature leaf drop and yellowing of leaves) occur in response to environmental stress and are highly visible to the public. Solar transmittance has potential as a surrogate for biomass estimates in that it is a nondestructive technique and is less time-consuming. (C.5)

Macroinvertebrate Abundance, Biomass, and Species Composition. Macroinvertebrates are sensitive to biological, chemical, and physical stressors. They are critical components of the food chain and support animal species of public concern. (C.6)

Soil and Aquatic Microbial Community Structure. Microbial communities are sensitive to some contaminants and are linked to fundamental ecological processes such as nutrient cycling and litter decomposition. (C.7)

Demographics: Animals. Population vigor is reflected in the recruitment of individuals into the breeding population and their subsequent survivorship. Parameters include age structure, sex ratio, fertility, mortality, survivorship, and dispersal; and such measurements are only appropriate for definite keystone species. (G1.2)

Morphological Asymmetry: Animals. The morphological variability in structures such as teeth and bones of bilaterally symmetrical organisms has been found to increase with exposure to chemical contaminants, hybridization, and inbreeding. This parameter would be an early-warning indicator of population-level responses to human-induced stresses. (G1.3)

5.2.4.2 *Exposure and Habitat Indicators for Wetlands*

Exposure and habitat indicators are used by EMAP to identify and quantify changes in exposure and physical habitat that are associated with changes in response indicators. Ten exposure and response indicators have been selected as research indicators, seven of which are recognized as having high-priority status.

High-Priority Research Indicators

Wetland Extent and Type Diversity. In addition to being a response indicator, changes in areal extent and diversity of vegetation types determine the quantity of habitat accessible to animal populations in a region.

Abundance, Diversity, and Species Composition of Vegetation. In addition to being a response indicator, these measures reflect the quality of animal habitat as opposed to pattern and extent measures, which reflect the quantity of habitat. (C.3)

Nutrients in Water and Sediments. A primary stress to wetlands is high nutrient loadings from urban and agricultural runoff and from sewage inflows. Unnaturally high nutrient loadings deleteriously affect plant species composition and, subsequently, animal populations. (C.8)

Chemical Contaminants in Water and Sediments. Measurement of contaminants in wetlands will provide a diagnostic tool for interpreting bioaccumulation data. Wetlands are important sinks for metals and organic compounds because most wetlands are recipients of urban and agricultural runoff, sewage, and other aquatic pollutants. (C.9)

Hydroperiod. Hydroperiod is defined as total days of inundation per year, and is the most significant controlling factor shaping wetland structure and function. It is also the factor most often manipulated by humans. Changes in hydroperiod have significant effects on species composition, nutrient pathways and rates of cycling, habitat quality, and gross production. (C.10)

Linear Classification and Physical Structure of Habitat. The distribution and disappearance of certain species is associated with critical features of their habitat. Many studies have also demonstrated the relationship between animal diversity and vertical vegetation profile. (G3.2)

Landscape Pattern. Landscape indicators, calculated from data derived from remote sensing, describe the spatial distribution of physical, biological, and cultural features across a geographic area. These spatial patterns directly reflect the available animal habitat as well as predict other functional attributes of wetlands, including ground water recharge, contaminant interception potential, and storm water detention. (G3.3-G3.8)

Other Research Indicators

Biomarkers. A desirable feature of a monitoring program would be to detect an organism's response to human-induced stresses at the biochemical and cellular level before the stresses produce a detectable response at the organism and population levels. Although the use of biomarkers as early-warning response indicators requires more basic research, their present value for regional survey monitoring is to provide information to support or refute hypotheses on why the ecological condition of wetlands is subnominal. (G2.1-G2.11)

Bioassays. One of the recognized functions of wetlands is their ability to filter pollutants from point and nonpoint sources. Excessive pollutant loading, however, can overwhelm the assimilative capacity of wetlands and result in degradation of their biological condition. The ability of wetlands to sustain healthy organisms can indicate the degree of wetland contamination. Bioassays involve placing an organism or population in the field or into "microcosms" constructed with materials from the field to be tested in the laboratory. (C.10)

Chemical Contaminants in Tissues. Measurements of contaminant bioaccumulation in plant and animal tissues would be an indicator of exposure to contaminants and should help explain why wetlands are in subnominal condition. (C.11)

5.2.5 Wetland Indicators Not Appropriate for EMAP

Response indicators of wetland condition for a regional and national program employing an index concept must include the following general characteristics:

- The suite of indicators must be limited in number. A national program for assessment of wetland condition cannot sample every constituent or structural component.
- Measurements must be integrative to detect condition. The chosen suite of indicators must integrate the broad spectrum of wetland resources and their responses to stressors.
- Measurements that require frequent sampling intervals or spatially intensive sampling techniques are inappropriate.
- Indicators must respond quickly to stressors. Long-lived components or those with exceptional capabilities of adapting to stressors may not be appropriate.

When evaluated by these criteria, many indicators proposed in the literature (Schaeffer et al. 1988; Brooks and Hughes 1988; Adamus et al. 1987; Chapman et al. 1987) are not suitable for EMAP. Others are clearly not appropriate because they are not ecologically significant in wetlands or are too complex to interpret. Similarly, some community-level indicators that are good measures of wetland condition also are inappropriate for EMAP. Community-level indicators have been proposed as the simplest and possibly most integrative of ecological indicators. Generally accepted community-level effects of changes in ecological condition can be grouped into five categories (after Schaeffer et al. [1988], and Rapport et al. [1985]): (1) decline in numbers of native species, (2) change in standing biomass, (3) change in net or gross primary production (4) change in pathways of nutrient cycling, and (5) retrogression.

The first community-level indicator listed above, decline in numbers of native species, is actually one metric of the high-priority research indicator "Abundance, Diversity, and Species Composition of Vegetation." Ratios of native vegetation species to exotic species are expected to be sensitive indicators of ecological stress. Within each of the other categories listed, however, measurements exist that could detect changes in wetland health, but because of measurement constraints, are inappropriate for a national program. For example, effects of stress may be exhibited as reduction in the size distribution of species (Rapport et al. 1985) and changes in the mechanisms of, and capacity for, damping undesirable oscillations (Schaeffer et al. 1988). Both of these phenomena are functional responses to stress, but development of indicators to assess their use in regional surveys would be difficult.

Primary production is an ambiguous measure of wetland condition, especially when quantified on a once-per-year basis. Net production is often measured by sampling vegetation at two different times and calculating the difference in standing biomass; a positive difference is interpreted as net production during the time interval. Annual growth rates as evidenced in tree-ring analysis may also be used as estimates of net production. Many ecosystems exhibit no net production, whereas others may exhibit significant accumulation of biomass in early stages of succession followed by declines to no net growth during later climax phases. As a result, net production is a poor indicator of ecological condition. In addition, net production measurements exhibit tremendous intrasite and intersite variability.

Gross primary production, while the most valuable indication of productivity, is difficult to measure in emergent vegetation. The most common method uses an infrared gas analyzer to measure the concentrations of carbon dioxide in air before and after it has passed through an ecosystem. A portion of the community (a twig with leaves, a whole tree, or a part of the entire community) is enclosed in a clear plastic tent, and air inflows and outflows are sampled. Many variables affect accuracy, so many, in fact, that it is impossible to detect changes in gross primary production that could be attributed to stressors. The complexity of measurement techniques, potential for conflicting results, and large intrasite and intersite variability eliminate gross production as a response indicator.

Direct measurement of nutrient cycling is exceptionally difficult in ecosystems that lack clearly defined input and output points necessary for mass balance equations. Nutrient export from a wetland watershed, either via forest clearcutting or because of altered hydrologic regimes, leads to significantly modified nutrient pathways. Similarly, declines in the abundance of consumers and decomposers can significantly alter nutrient cycling and may impair overall ecological function. Organic matter accretion, decomposition, and measures of microbial community structure are surrogates of nutrient cycling, which may indicate sustainability of a wetland.

Retrogression is a large-scale ecosystem change in the direction of earlier stages of succession. Retrogression is determined through measures of community organization and species composition. Although retrogression is not included as a wetlands research indicator, insofar as retrogression refers to changes in the successional stages of vegetation, it is indirectly included as an indicator of ecological condition.

Although many classes of animals (mammals, fish, reptiles, and amphibians) are an important component of wetlands, may serve as excellent bioaccumulators of contaminants, and are highly visible to the public, the EMAP sampling scheme may not permit their measurement in wetlands. Animal mobility, high degrees of spatial and temporal animal variability, and naturally variable wetland forcing functions compound the difficulties of quantifying animal community structure, especially with the EMAP survey approach. The authors suggest monitoring water birds and possibly small mammals such as muskrat. The suitability of monitoring other animal classes in wetlands is discussed in Section 9.2. The point count method is considered appropriate for monitoring birds in EMAP. This method is a means of obtaining indices of abundance for comparing bird populations of different habitats (or of the same habitat in different locations) during the index period (See Section 9.2). Monitoring water birds might require a specialized technique such as playback of vocalization because of low detectability; thus the inclusion of water birds as a wetland response indicator will be determined by the feasibility of such sampling under the design of EMAP. Even more difficult than determining changes in ecological condition is providing plausible explanations for changes in animal population sizes. For example, some mammal species are affected by hunting pressure or, because of their mobility, are subject to accidental death on roadways. These anthropogenic pressures result in fluctuations in animal populations that would have to be accounted for.

An alternative to measuring animal communities in wetlands would be for EMAP to monitor habitat (primarily for wetland-dependent birds and mammals) by using aerial imagery or wetland vegetation structure. Habitat and wetland vegetation structure could serve as indicators of herbivore productivity or habitat suitability. For example, aerial photographs could be examined for the presence of beaver or muskrat houses. Wetland habitat suitability could be modeled or approximated by using vegetation or landscape indicators (see Section 9.3), as suggested by the literature (Asherin et al. 1979; Klopatek et al. 1981; Christensen 1986). Landscape pattern is considered very important for monitoring the status of wetlands, and landscape indices are useful for indirectly monitoring animal habitat. Unfortunately, community effects due to toxicants and some other stressors would not be reflected in habitat measures. In addition, lag times are often noted between altered habitat and subsequent animal response.

5.3 APPLICATION OF WETLAND INDICATORS

If the ecological condition of regional wetland classes is to be determined, a threshold value that defines subnominal condition must be developed for each response indicator. The most promising short-term approach for setting subnominal thresholds (Section 2.3.2) for regional wetland classes (considering the wide variation among wetland classes), and that may provide needed baseline data for statistical classification, is the use of reference wetlands. Wetlands selected in the Tier 1 resource sample will be partitioned on the basis of surrounding landscape attributes into a continuum of landscape development intensities that range from relatively pristine to highly developed. Measurements of response indicators, along with landscape development intensities, will be used to define the subnominal threshold.

To determine the relative condition of wetlands, the characteristics of components (structure) and processes (function) in healthy wetlands must be known, but in many wetland classes, these have not been well defined. In addition, it is becoming increasingly difficult to find wetlands not obviously exposed to some hazard. Most wetlands are located in topographic low points, places that collect surface water runoff, and thus they are subjected to the various constituents carried by runoff. As a result, wetlands are affected by activities in the surrounding landscape so that few, if any, wetlands can be considered pristine (Schindler 1987). Thus, reference wetlands must be carefully selected to account for human alteration of landscapes that may have adversely affected the entire regional population of wetlands.

A basic challenge in interpreting data from wetland monitoring programs is distinguishing natural environmental fluctuations from signs of human-induced stress. What may be considered a normal variation in one wetland ecosystem or at one time interval may be interpreted as a response to low-level stress in another. Very little is known about these normal variations, termed "stability envelopes" (Duinker and Beanlands 1986). Of critical importance is establishing, with sufficient sampling and an adequate period of record, the stability envelope for different wetland classes.

5.4 RESEARCH NEEDS FOR EMAP-WETLANDS

5.4.1 Research Priorities

Two critical areas of research are needed to both meet the objectives of EMAP and increase the efficiency and reliability of the set of research indicators for inland wetlands. First, in the near term, small-scale field studies and regional demonstration projects will test whether the set of research indicators can yield unambiguous information. This project will involve testing measurement techniques, field protocols, and data analysis techniques. The second critical area of research is to increase the efficiency and reliability of the set of indicators for wetlands. Metrics most sensitive to changes in wetland condition must be identified. In particular, efforts should concentrate on developing sensitive vegetation and macroinvertebrate indices for detecting responses to stress.

Analysis of landscape indicators measured from remotely sensed data also need development and testing (see Section 9.4). A proposed index called the Landscape Development Intensity (LDI) index, which is a measure of developmental impact and therefore a possible indicator of potential ecological impacts, may provide a quick and cost-effective method for identifying populations of wetlands that are most likely to be subnominal. Further, the LDI may allow for landscape-scale classification. This in turn will quickly and economically enable the targeting of monitoring efforts within regions. The LDI has been applied in some preliminary work in Florida and has shown some promise in identifying threatened populations of wetlands in urbanizing landscapes (Brown and Kentula 1990). Further testing is needed to both expand its applicability by incorporating additional variables in the index and tailor its use and weighting system for identifying threatened wetlands over a region.

In the longer term, EMAP-Wetlands must support research on wetland structure to better understand stress pathways and their diagnosis. As this research is accomplished, significant advances can be made to develop response indicators, refine subnominal thresholds, and improve efficiency for detecting subnominal wetland populations.

5.4.2 Interaction with EMAP Resource Groups and Other Agencies

EMAP-Wetlands will coordinate efforts and assessments with several other EMAP resource groups whose resource categories are closely linked. For example, because wetlands both transform and filter contaminants carried in flowing waters, wetland presence and condition directly influence both inland surface water and near-coastal resources. Similarly, wetlands are important in arid landscapes because of their water storage and animal support functions. The EMAP resource category that currently represents the greatest potential hazard to wetlands is agroecosystems because of the threat of conversion of wetlands to agricultural lands.

In addition to coordinating with other EMAP resource groups, it has been essential for the success of EMAP-Wetlands to initiate coordination with the U.S. Fish and Wildlife Service's National Wetlands Inventory (NWI) on issues of statistical design and wetland classification. The NWI is currently mandated by Congress to monitor status and trends in wetland acreage. To date, only NWI publishes status and trends reports on wetlands; the "Status and Trends Survey of Wetlands and Deepwater Habitats in the Conterminous United States, 1950's to 1970's" (Frayer et al. 1983) represents the first comprehensive inventory of wetland acreage and wetland loss. The objective of the study was to develop national statistical estimates of wetland distribution and abundance for the lower 48 states during the 1950s and 1970s and to calculate the change over this period. The NWI survey was designed to develop national statistics that would, on the average, estimate with a probability of 90% the total acreage and change within 10% of the actual value of each wetland type. A network was also established for future monitoring. A current study will summarize status and trends in wetland acreage from the 1970s to the 1980s, and future studies will be conducted at 10-year intervals.

In addition to the discussions with NWI, we have communicated frequently over the past year with managers of the Breeding Bird Survey data base and several bird data bases housed at the Cornell Laboratory of Ornithology. We have also contacted more than 400 wetland scientists from government agencies, academic institutions, and the private sector and asked them to plot the locations of wetlands they have monitored. Contacts have been made to obtain wetlands-related data from the USDA Forest Service (wetland types covered by the Forest Inventory and Analysis program), Soil Conservation Service (National Resource Inventory), and Federal Emergency Management Agency (floodplain acreage estimates).

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SECTION 6

INDICATOR STRATEGY FOR FORESTS

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6.1 INTRODUCTION

A forested ecosystem includes the living organisms of the forest and extends from the top of the tree canopy to the lowest soil layers affected by biotic processes (Waring and Schlesinger 1985). This ecological definition determines the scope of the forest indicator strategy. Implementation of indicator measurements will require operational definitions of forests and resource categories.

Forests provide many amenities important to the social, economic, and cultural aspects of life. Statistics from a recent national assessment of forests (USDA-FS 1982) provide some indication of the extent and value of forests and why improved monitoring programs are supported by the public and Congress.

- Forests covered approximately 298 million hectares (737 million acres), or about one-third of the total land area in the United States.
- Employment for more than 3 million workers originated from forests, and in many rural locations, the primary employment sector was forest-related.
- The annual harvest of timber material was worth more than $6 billion, and timber-based economic activities were valued at more than $48 billion (4.1% of the gross national product).
- The social and cultural values of water, wetlands, and animals are often closely associated with, and are sometimes contingent upon, forested ecosystems.
- Although difficult to quantify, the social and cultural values of forests are tremendous.

6.1.1 Legislative Mandate for Forest Monitoring

Public and Congressional support for forest monitoring has a very long history relative to other ecological resources. Almost 100 years ago, the Organic Act of 1891 established the National Forests and included provisions for the inventory of these lands. Later, the Forestry Research (McSweeney-McNary) Act of 1928 required a current and comprehensive inventory and analysis of all of the nation's forest resources. This early legislation focused on timber inventory, and it was not until 1974 and the passage of the Forest and Rangeland Renewable Resources Planning Act (RPA) that much consideration was given to monitoring nontimber resources. Since passage of the RPA, Congress has passed the National Forest Management Act (1976), the Federal Land Policy and Management Act (1976), the Soil and Water Conservation Act (1977), and the Forest Ecosystems and Atmospheric Pollution Research Act (1988). These legislative acts share the following assignments (Lund 1986).

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- Preparation and maintenance of continuous natural resource inventories
- Coordination and cooperation among resource agencies and organizations to avoid duplication of inventory and planning efforts
- Determination of both current and potential changes in renewable natural resources
- Determination of resource interactions and management alternatives
- Submission to the nation of periodic assessment reports of the natural resources

Forest monitoring is also relevant for assessments made pursuant to other federal legislation, such as the Federal Insecticide, Fungicide, and Rodenticide Act, the National Environmental Policy Act, the Resource Conservation and Recovery Act, and the Endangered Species Act. An important trend in this legislation has been the increasing emphasis given to resources other than timber, such as animals, rangeland, water, and recreation, as valued components of the forest.

6.1.2 Forest Resource Classes

The EMAP resource classes defined for forests are based on major forest types. This classification system was proposed because forest condition and change appear to be directly associated with major forest type. The EMAP sampling design (Section 2.2), however, reserves the capability to poststratify by other criteria if more convenient for the analysis and interpretation of indicator data.

Twenty-two forest resource classes are currently identified:

1. Oak/Hickory
2. Oak/Gum/Cypress
3. Elm/Ash/Cottonwood
4. Maple/Beech/Birch
5. Aspen/Birch
6. Larch
7. Western Hardwood
8. Redwood
9. White/Red/Jack Pine
10. Spruce/Fir-Eastern
11. Longleaf/Slash Pine
12. Loblolly/Shortleaf Pine
13. Douglas Fir
14. Hemlock/Sitka Spruce
15. Ponderosa Pine
16. White Pine-Western
17. Lodgepole Pine
18. Fir/Spruce-Western
19. Pinyon/Juniper
20. Oak/Pine
21. Ohia
22. Spruce/Hardwood

6.2 IDENTIFICATION OF INDICATORS

Forests are open systems that exchange energy and materials with other resources, including adjacent forests, upstream and downstream nonforested ecosystems, and the atmosphere (Waring and Schlesinger 1985). Forests also host a diversity of inhabitants that take part in complex and interacting processes. These features complicate the task of identifying indicators of forest response, exposure, and habitat. Nevertheless, a National Research Council (NRC) committee reviewing biomarkers of air pollution stress and damage in forests concluded that the "knowledge of the structure and physiology of forests and trees is now sufficient to develop a basis for detecting disruption or disturbance from a variety of causes" (NRC 1989).

Surveys of forest stress and damage based on sets of indicators (such as the EMAP approach) are one element of an overall strategy recommended by the NRC committee to elucidate cause-and-effect relationships in forests. Many measurements could be considered for these surveys, but from a practical standpoint, not everything can be measured. Thus, it is essential that a strategy to identify indicators be stated clearly in the context of EMAP's goals and objectives (see Section 1).

The sequential strategy outlined in the four steps below is suggested to develop candidate indicators of forest condition and associated stresses.

1. Identify perceptions (including those of resource managers, scientists, private industry, legislators, and the general public) of forest condition.

2. Identify environmental values related to these public perceptions.

3. Identify environmental hazards, management actions, and natural phenomena that affect the environmental values.

4. Identify indicators that represent environmental values, address issues of concern, and satisfy the criteria of the EMAP design.

6.2.1 Perceptions of Forest Condition

The ecological condition of forests is perceived in a variety of ways. Common perceptions are based on the extent and distribution of forest lands for recreational use; the economic value of timber production; the maintenance of viable game populations; the yield of high-quality water; the ability of forests to recover from natural stresses such as insects, diseases, and fire; and the maintenance of diversity within and among species, ecosystems, and regional landscapes.

Within each of these general categories of concern, there are many more specific concerns. For example, some are concerned about the loss of old-growth forests and the reduction of habitat for certain species of birds, mammals, and amphibians that depend on old-growth forests (Franklin 1988). Others are concerned about the impact of decreasing forest cover in watersheds on the quality of water for public consumption and fisheries production.

Listing public perceptions of forest status can provide only a glimpse of what types of questions might be asked of a forest monitoring program. There are innumerable perceptions of specific values, and many of them cannot be anticipated. The identification of public perceptions can, however, suggest broad areas of concern to guide the indicator strategy. In the EMAP framework, such areas are expressed as environmental values.

6.2.2 Environmental Values for Forests

In the EMAP framework, environmental values relate the public perceptions of forest condition to forest resource attributes that can be measured. For example, the public perception of a healthy forest as one that can recover from insect infestation, disease, and other natural factors is one component of the "sustainability" value. But a term such as sustainability can have different meanings in the scientific community, and therefore it is difficult to determine what to measure. The choice of indicators, as surrogates for environmental values, defines the attributes of forest resources that will be measured (see also Section 2.1).

In addition to sustainability, other important values of forest condition include productivity, aesthetics, biodiversity, and extent. "Extent" refers to the distribution of particular species, populations, or communities such as forest types in a region. "Productivity" reflects the potential of the forest to utilize energy, the accumulation rate of stored energy, and the consumptive rate of stored energy to support life in the forest. "Aesthetics" is the enjoyment of scenery and recreation. "Biodiversity" encompasses genetic diversity, diversity of species within an ecosystem, and diversity of ecosystems and regional landscapes.

More effort is needed to identify environmental values. A thorough review of the scientific literature on topics such as hierarchy theory, disturbance, succession, and stability and steady-state concepts may allow a less ambiguous concept of ecological condition to be developed. Individuals will always have different perceptions of forests, and thus of how to describe their condition. For now, analysts must be sensitive to these differences; ultimately, we may be able to identify a set of values that relates to everyone's perceptions of forests.

6.2.3 Hazards to Forest Ecosystems

Forests everywhere are under continual and variable stress from a variety of natural and human-related sources. The major human-induced hazards are global climate change, chemical pollution (particularly in the atmosphere), and land-use change. Relatively rapid changes in global climate may occur as a result of increases in the concentrations of trace gases in the atmosphere (NAS 1983), which ultimately may have severe ecological consequences (Abrahamson 1989). Pollution stresses of concern include ozone, acid deposition, and airborne toxins (McLaughlin 1985; AFA 1987; NAPAP 1988). Land uses such as urbanization and agricultural development may reduce forest acreage or alter the biotic integrity of forests. Resource management practices may alter biodiversity, species distributions, and other forest attributes. The relative importance of these hazards will vary by forest class and geographic region.

6.2.4 Forest Indicators Appropriate for EMAP

No widely accepted definition of forest health or integrity exists. An almost unlimited number of potential measurements of forests could be considered for monitoring. Many candidate indicators can be identified from existing monitoring systems (e.g., NSEPB 1985; USDA-FS 1985; UNEP and UN-ECE 1987; Magasi 1988), from symposia (e.g., Ågren 1984; Schmid-Haas 1985), from technical publications (e.g., Materna 1984; Smith 1984; Waring 1984; Schaeffer et al. 1988), and from workshops and committee reports (e.g., Alexander and Carlson 1988; NRC 1989).

The EMAP indicator selection process for forests began in July 1989 with a preliminary identification of about 150 candidate indicators from the literature. The list was augmented, and indicators were screened according to feasibility and appropriateness in the EMAP context, at a workshop in late July 1989. A draft report that identified 17 (mainly response) indicators was prepared from the results of the workshop. The draft report was circulated for comments and discussed at a second workshop in late August 1989.

The objectives of the second workshop were to reach a consensus on the recommended indicators and to add technical data for the indicator fact sheets (Appendix D). The emphasis was to identify a consensus set of highly feasible and interpretable response indicators. A reduced list of eight indicators resulted from the workshop. Indicators were added later in response to both information on indicators that are applicable to multiple resource categories (Section 9) and the suggestions of reviewers who participated in a written external peer review (Appendix I.8) in April 1990. A review was also conducted by the EPA Science Advisory Board in May 1990.

During this selection process, candidate indicators were ranked according to the EMAP indicator selection criteria (Table 6-1). These rankings are partly subjective, and different individuals could develop other rankings based on differences in background, experience, and perception. It is important to note that not

Table 6-1. Evaluation of Some Candidate Indicators for Forests by EMAP Selection Criteria (H = High, M = Medium, L = Low)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	**Cost Effective**[12]
Selected as Research Indicators												
Tree Growth Efficiency	H	H	H	H	M	H	H	H	M	M	L	M
Visual Symptoms	H	H	M	H	H	M	H	H	H	M	M	H
Nitrogen Export	H	H	M	M	L	H	H	H	M	M	H	L
Litter Dynamics	H	H	H	L	M	H	H	M	M	M	M	M
Microbial Biomass/ Respiration: Soils	H	H	M	M	L	L	H	H	H	L	M	M
Veg. Abund./ Species Composition	M	M	H	H	H	H	H	H	H	M	H	H
Nutrients in Foliage	H	H	M	L	M	H	H	M	M	L	H	M
Contaminants in Foliage	M	H	M	H	M	M	H	M	M	L	M	M
Soil Productivity Index	H	H	H	M	H	H	H	H	H	M	H	H
Stable Isotopes	H	H	H	L	L	M	H	M	L	L	L	L
Bioassay: Moss/Lichen	H	H	H	H	H	M	H	H	M	M	M	H
Carbohydrates/ Secondary Chemicals	M	H	H	L	L	H	H	M	L	L	L	L
Considered but Not Selected												
Individual Plant Physiology	H	H	L	L	L	H	H	L	M	M	M	L
Histology/Histochemistry	H	H	M	M	L	M	M	L	M	M	M	L
Soil Water Chemistry	H	H	M	M	L	M	M	M	M	L	M	L
Phenology	M	M	M	M	L	H	H	L	M	L	M	M
Non-Native Indicator Plants	M	H	H	L	L	M	H	M	M	M	M	L
Genetics	M	H	H	M	L	H	M	L	M	L	M	L

[1] Correlates with changes in processes or other unmeasured components.
[2] Applies to a broad range of regional ecosystem classes.
[3] Integrates effects over time and space.
[4] Relates unambiguously and monotonically to an endpoint, a relevant exposure or habitat variable.
[5] Can be quantified by synoptic monitoring or by automated monitoring in a cost effective manner.
[6] Is important to the overall structure and function of ecosystems.
[7] Responds to stressors of concern or management strategies.
[8] Is anticipatory by providing an early warning to widespread changes.
[9] Has a standard method of measurement.
[10] Exhibits low measurement error.
[11] Has a historical data base or the capability of being generated from accessible data sources.
[12] Is cost effective (has low cost and high information value).

even the high-priority research indicators are ready for implementation; an important lesson from the indicator selection process is that much remains to be done to improve the feasibility and interpretability of regional forest monitoring.

The designation of indicators as either response, exposure, or habitat is necessary to develop an integrated and concise summary of recommendations in the EMAP framework. We expect that, in the future, the designation of some indicators may be changed, perhaps to more than one indicator type. For example, while *soil productivity index* is currently listed as an exposure and habitat indicator, soil productivity could conceivably be considered a response indicator (see also Section 7). Better definition of environmental values will enable a better designation of indicator types.

A brief description of each research indicator (Figure 6-1) is given here. More detailed descriptions of the indicators, their application, suitable index period, variability, and research needs are listed in Appendices C, D, and G, as referenced by the code in parentheses that follows each description below.

6.2.4.1 *Response Indicators for Forests*

Response indicators are used by EMAP to quantify and classify the condition of ecological resource classes. Nine response indicators have been selected as research indicators for forests, three of which are recognized as having high-priority status.

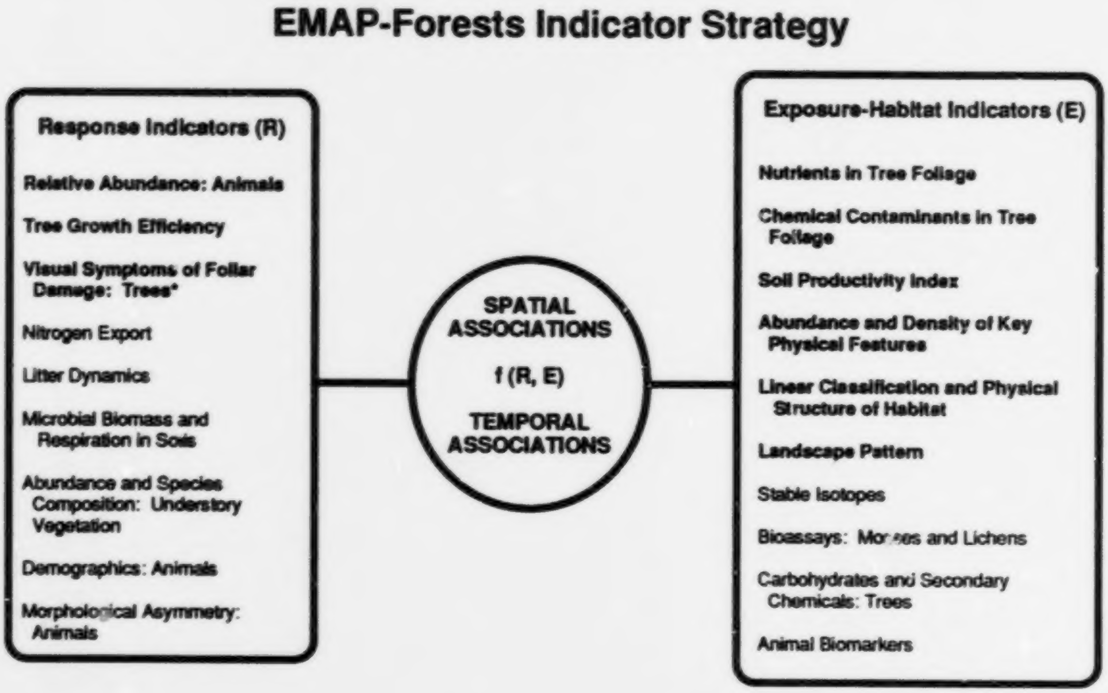
EMAP-Forests Indicator Strategy
Response Indicators (R)
Relative Abundance: Animals
Tree Growth Efficiency
Visual Symptoms of Foliar Damage: Trees*
Nitrogen Export
Litter Dynamics
Microbial Biomass and Respiration in Soils
Abundance and Species Composition: Understory Vegetation
Demographics: Animals
Morphological Asymmetry: Animals
SPATIAL ASSOCIATIONS
f (R, E)
TEMPORAL ASSOCIATIONS
Exposure-Habitat Indicators (E)
Nutrients in Tree Foliage
Chemical Contaminants in Tree Foliage
Soil Productivity Index
Abundance and Density of Key Physical Features
Linear Classification and Physical Structure of Habitat
Landscape Pattern
Stable Isotopes
Bioassays: Mosses and Lichens
Carbohydrates and Secondary Chemicals: Trees
Animal Biomarkers

Figure 6-1. Diagram of the proposed EMAP-Forests Indicator Strategy. Indicators in bold are high-priority research indicators. Response indicators with an asterisk (*) also could function as exposure and habitat indicators.

High-Priority Research Indicators

Relative Abundance: Animals. The status of a community of organisms can sometimes be assessed by the status of a few species or types of species that play critical roles. Some types of birds could be used as indicators that integrate across resource classes, whereas small mammals, reptiles, and amphibians generally would serve to monitor condition within a resource class. (G1.1)

Tree Growth Efficiency. Tree growth efficiency is a measure of the overall ability of trees to maintain themselves in an ecosystem, which is an obvious but sometimes overlooked condition for the perpetuation of forests. Measurements of periodic tree dimensional or biomass growth, and an index of capacity for growth, are used to construct an integrative index. (D.1)

Visual Symptoms of Foliar Damage: Trees. Visual symptoms are measures of the health of individual trees and populations in terms of pathological conditions, and they are measures of aesthetic quality. Defoliation and discoloration of foliage can be used to construct an overall index of forest condition. (D.2)

Other Research Indicators

Nitrogen Export. The export of nitrogen, which is usually conserved in terrestrial ecosystems, is generally considered to be an indicator of damage or change in forest structure, function, or composition. Unfortunately, nitrogen export from forests cannot be effectively measured in a survey. An indicator needs to be developed so that nitrogen exports that are measured during an index period truly reflect the overall forest response to stresses. (D.3)

Litter Dynamics. The rates and pathways of forest litter decomposition and recycling are important indicators of the continued health and productivity of forests. Unfortunately, constructing an index of litter dynamics is complex. It may be possible to develop indices based on litter chemistry or decomposition rate.

Microbial Biomass and Respiration in Soils. Soil microorganisms play a vital role in the retention and release of nutrients in forest soils and can be sensitive to changes in forest condition. Microbial biomass and mycorrhizal density, for example, may help to link vegetative responses to soil productivity. (D.10)

Abundance and Species Composition: Understory Vegetation. Understory vegetation can be a sensitive indicator of forest responses to environmental stresses. Measures of the amount and distribution of various life-forms can be summarized into useful indices. For this research indicator, reference is made to an analogous indicator that would be used to monitor wetlands vegetation. (C.3)

Demographics: Animals. Population vigor is reflected in the recruitment of individuals into the breeding population and their subsequent survivorship. Parameters include age structure, sex ratio, fertility, mortality, survivorship, and dispersal; and such measurements are only appropriate for definite keystone species. (G1.2)

Morphological Asymmetry: Animals. The morphological variability in structures such as teeth and bones of bilaterally symmetrical organisms has been found to increase with exposure to chemical contaminants, hybridization, and inbreeding. This parameter would be an early-warning indicator of population-level responses to human-induced stresses. (G1.3)

6.2.4.2 *Exposure and Habitat Indicators for Forests*

Exposure and habitat indicators are used by EMAP to identify and quantify changes in exposure and physical habitat that are associated with changes in response indicators. Ten exposure and habitat indicators have been selected as research indicators for forests, five of which are recognized as having high-priority status.

High-Priority Research Indicators

Visual Symptoms of Foliar Damage: Trees. Visible symptoms may indicate a plausible mechanism of subnominal forest condition on tree foliage. (D.2)

Nutrients in Tree Foliage. Nominal forest condition depends on a sufficient supply and the proper balance of critical nutrients in foliage. Imbalances may signal imbalances in forest processes or indicate exposure to specific types of stresses. It may be possible to construct a composite index of foliar nutrient concentrations to measure imbalance, and to disaggregate the composite index into individual nutrient concentrations for more detailed analyses. (D.5)

Chemical Contaminants in Tree Foliage. Measurements of chemical contaminants can identify toxic levels of elements and the occurrence of toxic anthropogenic compounds. Detection of certain contaminants in foliage can provide information on possible mechanisms by which changes in forest condition might occur. (D.6)

Soil Productivity Index. Chemical imbalances in the soil can signal changes in ecosystem function and indicate exposure to specific types of stresses. Roots may be damaged directly, and indirect effects can occur through decreases in nutrient availability or stresses on beneficial microbial populations. Erosion and moisture characteristics are examples of physical characteristics that affect soil productivity. It may be possible to construct an index of physiochemical soil factors which may be disaggregated into individual metrics for more detailed analyses. (D.7)

Abundance and Density of Key Physical Features. Certain physical features of habitats (e.g., cliffs, outcrops, sinks, seeps, talus slopes) are critical to animal diversity and abundance. Land-use practices can alter the density and distribution of many key physical features. Many habitat features are specific to particular resource classes, but determining what to measure in a given class can be based on existing literature. (G3.1).

Linear Classification and Physical Structure of Habitat. The distribution and disappearance of certain species is associated with critical features of their habitat. For example, overgrazing can result in the elimination of palatable understory species, compaction of forest soil, and conversion to open shrublands and grasslands. Species that depend on forest habitat may not be able to survive in a habitat that is predominately grassland. Many studies have also demonstrated the relationship between animal diversity and vertical vegetation profile. (G3.2)

Landscape Pattern. Landscape indicators, calculated from data derived from remote sensing, describe the spatial distribution of physical, biological, and cultural features across a geographic area. Thus, these indicators are used to generally quantify resource structure, including habitat proportions, patch size, diversity, and contagion. Landscape pattern has been correlated to disturbance and animal habitat or presence. (G3.3-G3.8)

Other Research Indicators

Stable Isotopes. Certain ratios of stable isotopes in plant tissue can be used to distinguish possible effects of climate from those of pollutants. Reliable quantitative analyses and interpretations are not possible without further study of natural variation and specific responses to particular stresses. In addition, standard sampling and measurement techniques need to be developed. (D.8)

Bioassays: Mosses and Lichens. Mosses and lichens, which derive nutrition directly from the atmosphere and act as filters for and accumulators of contaminants, have been utilized in several European monitoring programs. Although mosses and lichens can serve as a binary (yes or no) indicator of contaminant exposure, their use has been criticized because the contaminant uptake and loss rates are not known, and total accumulation is thus difficult to estimate. (D.9)

Carbohydrates and Secondary Chemicals: Trees. Starch reserves have low priority in carbohydrate allocation, and reductions indicate either a lower total assimilation or less efficient assimilation of carbon which, in turn, is indicative of or related to nutrient imbalance or other stressors such as soil contaminants. Secondary chemicals (e.g., chemicals produced for defense against herbivores) require relatively large amounts of energy to produce, and certain types are produced in larger quantities under certain types of stresses. Development of standardized testing and interpretive methods is needed. (D.11)

Animal Biomarkers. A desirable feature of a monitoring program would be to detect an organism's response to human-induced stresses at the biochemical and cellular level before the stresses produce a detectable response at the organism and population levels. Although the use of biomarkers as early-warning response indicators requires more basic research, their present value for regional survey monitoring is to provide information to support or refute hypotheses on why ecological condition of forests is subnominal. (G2.1-G2.11)

6.2.5 Forest Indicators Not Appropriate for EMAP

During the initial evaluation of candidate forest indicators with criteria similar to the EMAP indicator selection criteria (Table 6-1), it was easy to endorse some indicators and to eliminate many others from further consideration. But many candidate indicators need to be evaluated more completely. It is expected that the failure to propose certain candidate indicators as research indicators will cause scientists from diverse backgrounds to promote and defend them. This feedback will be a constructive part of EMAP's development of indicators.

To help guide further evaluation of indicators of forest condition, the following criteria could be considered (after Schaeffer et al. 1988).

- Is not dependent upon the presence, absence, or condition of a single species
- Is not dependent upon a census or inventory of many species
- Reflects knowledge of "normal" changes, for example, due to succession or other sequential changes
- Is one of several indicators that collectively represent a set of environmental values, but is not redundant
- Is dimensionless, single-valued, and monotonic in relation to a defined range of condition
- Has known statistical properties
- Responds to stresses but not to poor sampling design
- Is practical and feasible
- Is comparable among classes of forests, for example, among forest type, size, and density classes

- Integrates responses and has a stable value for several months each year and over a geographic area as large as a forest sampling unit

6.3 APPLICATION OF FOREST INDICATORS

Response indicators are used to identify forests in subnominal condition. Numeric criteria, regional reference sites, and classification have been suggested (Section 2.3.3) as approaches to defining subnominal threshold values for response indicators. Numeric criteria based on experience and expert judgement are available for use as subnominal thresholds for the high-priority response indicators, but these are difficult to justify objectively. This approach seems appropriate as a starting point when no better information exists. The development of threshold values based on regional reference sites can be recommended for the other response indicators and for comparison to thresholds based on numeric criteria. The classification approach can always be applied retrospectively once a complete data set is available.

As starting points, the subnominal thresholds for the suggested high-priority indicators can be developed based on the accepted definitions and experiences of existing monitoring systems. For example, the United Nations' Environment Program and its Economic Commission for Europe (UNEP and UN-ECE 1987) provides guidelines for the indicator of visual symptoms of foliar damage in trees, and the literature indicates that certain levels of tree growth efficiency are associated with the probability of insect attack (e.g., Mitchell et al. 1983) and mortality (Matson and Boone 1984). These starting points can be refined with additional experience or research.

An approach to defining subnominal thresholds that requires further development is based on simulation models of forested ecosystems. Although this option can potentially consider the full range of impacts to forest ecosystems, current understanding of forest processes as they relate to nominal structure, function, and composition does not permit construction or verification of models for all forest types in all regions.

Analysis and interpretation of indicators is tied intimately to the classification scheme. Even when conditions are "normal" everywhere, the same indicator may take on a different value in different forest classes. While many indicators meet the criteria of comparability among forest classes, those that do not could be analyzed separately for each class. An alternative approach that does permit direct comparisons among dissimilar forest classes is the normalization of indicators to class-specific baselines, which could be estimated from experience or from simulation models.

We did not investigate multivariate applications of indicators. As a starting point for application of response indicators, the maximum/minimum operator approach (Section 2.3.3) can be suggested. With this approach, each response indicator is evaluated separately, and a subnominal score for any one indicator effectively classifies the sampled location as subnominal. Refinements to this technique are possible, and the specific approach depends on the degree of independence among response indicators and the relative weights assigned to each environmental value.

Indices of forest condition and stress were considered as part of the indicator evaluation process. Two approaches are possible to identify integrative measures of forest condition and stress. The first involves the measurement of biologically integrative indicators, for example, growth (D.1) and visual symptoms (D.2). The second approach involves constructing a mathematically integrative index from several measurements, for example, as was suggested for soil (D.8) and foliar chemicals (D.7). Each step in any aggregation process is expected to result in some loss of specific information. Indices should be developed so that they can be broken into separate metrics (and scores) to diagnose possible causes and better interpret biological responses.

6.4 RESEARCH NEEDS FOR EMAP-FORESTS

Many topics for research were suggested during the indicator evaluation process. The topics ranged from investigations of specific indicators to the development of an overall strategy to guide further identification and testing of indicators. Much needs to be done to improve our capabilities for monitoring forest condition and forest stresses, and to make monitoring data more interpretable for a wider variety of policy questions. A few possibilities are mentioned here.

Considering the earlier definition of "forested ecosystem" (Section 6.1), the scope of indicators needs to be expanded. The lower priority research indicators (Figure 6-1) are a start in this direction. Research also needs to be focused on the analysis of indicators, alone and in combination, to detect and interpret the signals of change in forest condition.

Many measurements that could be used to indicate forest condition and stresses are made "off-frame," that is, at locations other than those sampled by EMAP. Examples include ongoing monitoring programs that measure air pollutants, insect and disease infestations, timber inventory, and satellite imagery. By building linkages to these auxiliary data bases, it may be possible to improve the interpretations of regional status and trends of forest condition.

Forests are just one category of terrestrial resources. Where appropriate, the indicators suggested for forests should be comparable to indicators suggested for other categories of terrestrial resources. For example, similar types of measurements of nontree vegetation, soil chemistry, productivity, and pathology have been recommended for forests, arid lands (Section 7), and agroecosystems (Section 8). The measurements are associated with indicators that differ not so much in substance as in name and method of measurement. An important part of EMAP forest indicator strategy will be the evaluation of research indicators for other EMAP resource categories with a view toward integration and refinement of forest indicators.

Finally, since forest field measurements are expensive, it is important to improve the efficiency of monitoring. A high priority should be placed on the identification and use of emerging technologies such as remote sensing that could markedly improve measurement efficiency and the ability to interpret measured indicators.

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SECTION 7

INDICATOR STRATEGY FOR ARID LANDS

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7.1 INTRODUCTION

The most diverse EMAP resource category consists of the grasslands, shrublands, woodlands, and tundra, collectively called arid lands. The resource classes identified for this category were intended to be both hierarchical and comprehensive and were designed to include all terrestrial resources not part of the EMAP wetland, forest, or agroecosystem categories.

Nineteen resource classes have been identified, ranging from barren to those covered extensively by vegetation:

1. Unvegetated
2. Steppe Grassland - Spring Green-up
3. Steppe Grassland - Summer Green-up
4. Prairie Grassland - Spring Green-up
5. Prairie Grassland - Summer Green-up
6. Savanna - Spring Green-up
7. Savanna - Summer Green-up
8. Chaparral/Shrub-Dominated
9. Chaparral/Shrub-Tree
10. Shrubland - Sagebrush (*Artemesia*)-Dominated
11. Shrubland - Blackbrush (*Coleogyne*)-Dominated
12. Shrubland - Creosote bush (*Larrea*)-Dominated
13. Shrubland - Saltbush (*Atriplex*)-Dominated
14. Shrubland - Microphyllous Scrub-Dominated
15. Shrubland - Whitethorn (*Acacia*)-Dominated
16. Woodland - Evergreen
17. Woodland - Deciduous
18. Tundra
19. Riparian

The classification scheme for this category is a modification of several previously developed classification systems (e.g., Brown et al. 1979; Mouat and Johnson 1978; Mouat et al. 1981).

In the conterminous United States, these resource classes occupy most of the land surface area (excluding forests at higher elevations) west of latitude 95°W. This western region contains important commercial, agricultural (e.g., grazing), mineral, and energy resources. Species (including man) occupying this region, however, depend upon (and are adapted to) the limited, but reliable, surface and ground water supplies. Because of dramatic population increases over the past 20 years, especially in western sunbelt states (particularly California, Nevada, and Arizona), the ecological resources in arid regions are experiencing increasing environmental pressures, including competition for water.

Some of the most unique plant and animal species inhabit these arid and semiarid regions. Of the eight states with the highest number of rare, threatened, or endangered plant and vertebrate species, six and three respectively, are western states. Increasing utilization (urbanization), resource development (mining), and careless management (overgrazing) of arid ecosystems have contributed to desertification and destruction of natural habitats. Declines of species such as the desert tortoise, bighorn sheep, desert pupfish, California condor, saguaro cactus, and Joshua tree may indicate that these resources are being affected by changes in land use, air quality (ozone, air toxics, sulfur dioxide), and water quality (increased salinity, pesticides, ground water withdrawal, hazardous waste contamination).

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Because arid ecosystems are so closely linked to water resource availability, they may be severely impacted by global climate change. A recent study found that arid ecosystems are perhaps the most susceptible of resource categories to global climate change because of attendant potential changes in water cycles (EOS 1989). Vegetation within these ecosystems is also susceptible to potential effects of climate change, particularly temperature. Temperature effects on plant growth are well established (Wang 1960). Most metabolic activities are restricted to a range of about 5°C of the optimum temperature for each plant species (Sosebee and Wan 1988). Many plant species, particularly those in the Great Basin, have been shown to be unable to acclimate to temperature changes (Caldwell 1985). Small shifts in temperature, combined with decreased moisture availability or other stress, thus can exacerbate effects or ecological condition. In addition, there is clearly the potential for adjacent forests to become "desertified" with global warming and changes in precipitation regimes.

Gradual changes in climate coupled with extensive human utilization may result in substantial degradation of arid land and water resources. Projected temperature increases, changes in precipitation patterns, and increasing demands for high-quality water will place heavy political, social, and economic pressures on government and industry nationally and worldwide. An active and effective regional monitoring program can identify and document environmental changes and establish ecologically sound guidelines for air, water, and natural resource management in arid and semiarid lands.

As discussed above, critical environmental issues facing arid and semiarid ecosystems include global change, desertification, air quality, and water resource management. Although global change and air quality concerns are relatively new issues, desertification and water resource management have been important issues since man first occupied arid and semiarid regions. The hunting of large mammals, gathering and transporting of seeds, and development of extensive irrigation systems by the native people in these regions had a profound effect on the landscape and the associated biological populations (Bender 1982). The introduction of livestock, further development of irrigation systems, and the increase in human populations has continued to place pressure on arid resources on a global scale.

Important environmental values associated with these issues include aesthetics, biodiversity, productivity, and sustainability. The unique nature of arid species and habitats, the concern over the importance of arid ecosystems to global climate, and the apparent increasing rate and extent of desertification in arid regions have led to an increased awareness on the value of these arid resources. Specific resources and habitats, such as riparian vegetation communities, are continually being threatened and decreasing to the extent that they are being lost entirely from the landscape. Development of indicators to monitor and assess the status and trends in the condition of these important resources will be critical in maintaining arid ecosystem function.

7.2 IDENTIFICATION OF ARID LAND INDICATORS

The research indicators for arid lands were developed through a series of workshops and interactive meetings between EMAP-Arid Lands members and scientific representatives of natural resource agencies who manage arid ecosystems. Two workshops were held in September 1989 and January 1990 which assembled more than 50 recognized experts (Appendix I) with backgrounds in plant and animal biology, ecology, soil biogeochemistry, animal life management, statistics, remote sensing, geobotany, microbiology, air and water quality, soil science, and other related disciplines. These experts represented governmental, private, and international institutions. The candidate indicators were compiled by several working groups at the workshops and presented for review to all participants. Facts sheets for indicators that satisfied the EMAP indicator selection criteria (Table 7-1) were subsequently written by selected authors and sent to participants for review. Comments were incorporated into the final indicator report. A written external peer review of these indicators was performed in April 1990 (Appendix I.8), followed by a review by the EPA Science Advisory Board in May 1990. The second workshop also confirmed four key issues for arid resources that will be

Table 7-1. Evaluation of Candidate Indicators for Arid Lands by EMAP Selection Criteria (H = High, M = Medium, L = Low)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	**Cost Effective**[12]
Selected as Research Indicators												
Vegetation Biomass	H	H	H	H	H	H	M	H	H	M	M	H
Riparian Extent	H	M	H	H	H	H	M	H	M	H	M	H
Energy Balance	H	H	H	M	H	H	H	H	M	M	M	H
Water Balance	H	H	H	H	H	H	H	H	M	M	M	H
Soil Erosion	M	M	M	L	H	M	M	M	L	M	L	M
Charcoal Record	H	H	M	M	L	H	M	L	M	M	H	M
Species Comp./Ecotone	H	H	H	H	H	H	M	M	M	M	H	H
Dendrochronology	H	H	H	H	L	H	H	L	H	H	H M	H
Pollen	M	H	M	M	L	H	H	L	M	M	H	M
Woodrat Midden	H	H	M	M	L	H	M	L	M	M	H	H
Abundance/Spp. Comp.: Lichens/Cryptogenic Crusts	M	M	M	L	M	M	H	M	M	M	L	H
Foliar Chemistry	M	M	M	M	L	M	M	M	M	M	L	M
Physiochemical Soil Factors	M	M	M	L	L	M	M	M	M	M	L	M
Exotic Plants	H	H	M	M	H	H	H	H	H	M	M	H
Livestock Grazing	M	M	M	H	H	H	H	L	L	L	L	M
Fire Regime	M	H	M	M	H	M	M	M	M	M	M	M

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Table 7-1. (Continued)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	**Cost Effective**[12]
Mechanical Disturbance: Soils/Veg.	H	L	M	M	H	H	L	L	L	L	L	M
Biomarkers	M	M	M	M	L	M	M	M	L	L	L	M
Chemical Contaminants in Wood	M	L	M	L	L	M	M	L	L	L	L	M
Considered but not Selected												
Microbial Biomass: Soils	M	L	L	L	L	M	H	H	L	L	L	L
Seed Production	M	M	L	M	L	M	M	L	M	L	L	L
C,H,O Isotope Ratios	M	M	H	M	L	M	H	L	L	L	L	H
Visual Symptoms: Foliage	L	L	L	M	H	L	M	L	L	L	L	L
Lignin/Cellulose Chlorophyll/N Ratios	M	H	M	L	H	M	M	M	M	L	L	M
Plant Pigments	M	H	M	M	H	M	H	M	L	L	L	L

1 Correlates with changes in processes or other unmeasured components.
2 Applies to a broad range of regional ecosystem classes.
3 Integrates effects over time and space.
4 Relates unambiguously and monotonically to an endpoint, a relevant exposure or habitat variable.
5 Can be quantified by synoptic monitoring or by automated monitoring in a cost effective manner.
6 Is important to the overall structure and function of ecosystems.

7 Responds to stressors of concern or management strategies.
8 Is anticipatory by providing an early warning to widespread changes.
9 Has a standard method of measurement.
10 Exhibits low measurement error.
11 Has a historical data base or the capability of being generated from accessible data sources.
12 Is cost effective (has low cost and high information value).

addressed by the indicators. These were desertification, global climate change, biodiversity, and degradation or loss of riparian communities.

7.2.1 Arid Land Indicators Appropriate for EMAP

This section summarizes the provisional set of response indicators and exposure and habitat indicators for arid lands in the conterminous United States (Figure 7-1). Indicators for the tundra resource class, located exclusively in Alaska, were not evaluated in this initial phase of EMAP indicator development. The research indicators will be used to detect and quantify status and trends in ecological condition of arid resource classes and to provide plausible explanations of changing condition. Many of the indicators will be employed spatially within a probabilistic framework. Others, however, will census entire regions, and still others will be retrospective in assessing past trends in time and space. The retrospective indicators will be used to examine natural phenomena and help quantify natural variation.

The selection of some research indicators for arid lands as high-priority (Figure 7-1), although necessarily subjective, was based on our review of the literature and experience with desert and grassland monitoring programs. Their measurement techniques often have not been thoroughly standardized or tested, or some question exists about whether they are sufficiently sensitive or applicable to all arid resource classes. Small-scale field tests and regional demonstration projects will further develop standardized protocols.

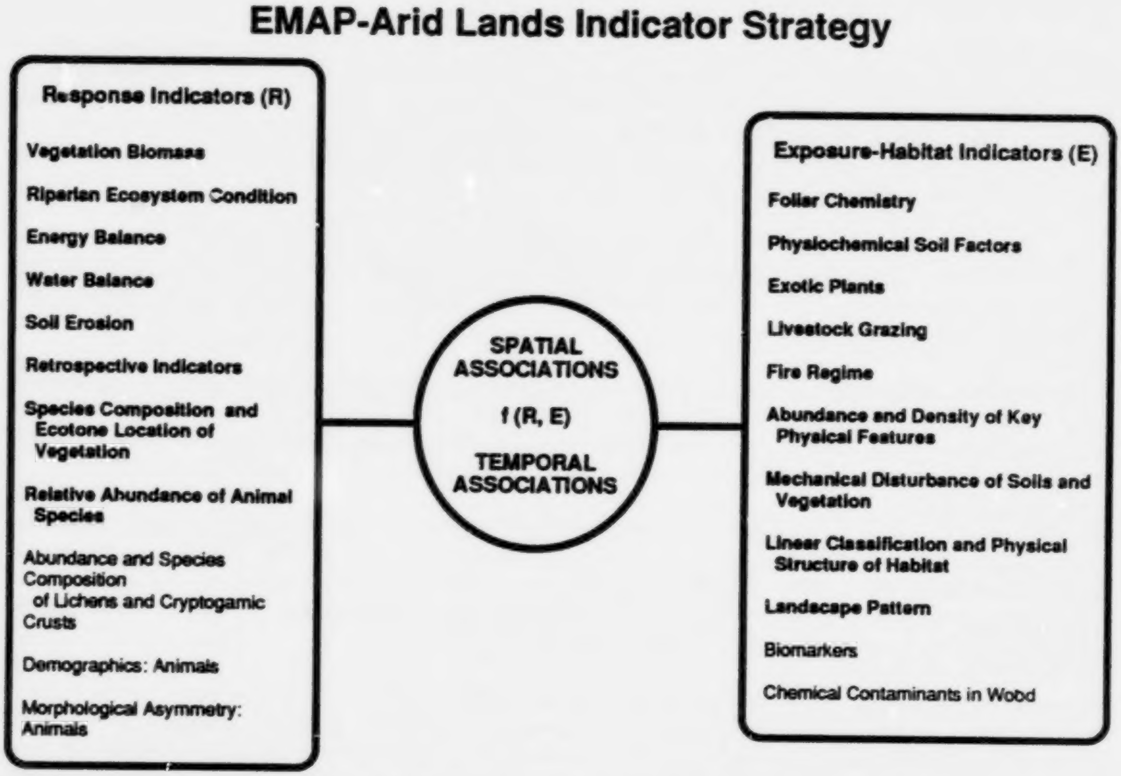
EMAP-Arid Lands Indicator Strategy
Response Indicators (R)
Vegetation Biomass
Riparian Ecosystem Condition
Energy Balance
Water Balance
Soil Erosion
Retrospective Indicators
Species Composition and Ecotone Location of Vegetation
Relative Abundance of Animal Species
Abundance and Species Composition of Lichens and Cryptogamic Crusts
Demographics: Animals
Morphological Asymmetry: Animals
SPATIAL ASSOCIATIONS
f (R, E)
TEMPORAL ASSOCIATIONS
Exposure-Habitat Indicators (E)
Foliar Chemistry
Physiochemical Soil Factors
Exotic Plants
Livestock Grazing
Fire Regime
Abundance and Density of Key Physical Features
Mechanical Disturbance of Soils and Vegetation
Linear Classification and Physical Structure of Habitat
Landscape Pattern
Biomarkers
Chemical Contaminants in Wood

Figure 7-1. Diagram of the proposed EMAP-Arid Lands Indicator Strategy. Indicators in bold lettering are core indicators.

A brief description of each research indicator is given here. More detailed descriptions of the indicators, their application, suitable index period, variability, and research needs are listed in Appendices E and G, as referenced by the code in parentheses at the end of each description below.

7.2.1.1 *Response Indicators for Arid Lands*

Response indicators are used by EMAP to quantify and classify the condition of ecological resource classes. Eleven response indicators have been selected as research indicators for arid lands, eight of which are recognized as having high-priority status.

High-Priority Research Indicators

Vegetation Biomass. Productivity and amount of green vegetation will be used as an indicator of condition of arid and semiarid vegetation. Biomass indices to be developed include measures of productivity, leaf area index (LAI), and greenness (calculated by using red and near infrared data from satellite images). The utility of remote sensing for measuring major vegetation responses to stressors on a regional scale is documented by Asrar et al. (1985), Tucker et al. (1985), and Becker and Choudhury (1988). Recent work by Elvidge and Mouat (1989) indicates that with data of high spectral resolution (10-nm-wide bands or smaller) it is possible to detect and monitor trace quantities of green vegetation at a site with less than 5% green plant cover, based on the chlorophyll red edge at 0.7 μm. Data from satellite sensors having high spectral resolution will be available in about 10 years. Integration of remote-sensing data with productivity measurements in the field will allow the determination of extent and distribution of productivity changes. (E.1)

Riparian Extent. The special aesthetic and functional value of riparian resources in arid and semiarid regions calls for an indicator to measure and track their integrity (Johnson and Simpson 1988). Riparian zones in the western United States have been widely degraded by improper grazing (U.S. GAO 1988b), water diversion, and watershed disturbance. Measurements of areal extent of the riparian zone, in combination with other response indicators such as vegetation structure (G3.2) and species composition (E.7), will indicate the condition of this important resource class. (E.2)

Energy Balance. Processes associated with desertification result in increased albedo or brightness of land surfaces when they are observed with satellite sensors. By coupling ground-based meteorological data with remotely sensed albedo and temperature measurements, it is possible to monitor the energy balance of a region (e.g., Vukovich et al. 1987). (E.3)

Water Balance. This indicator includes measurements of water inputs (precipitation, ground- and surface-water flows), outputs (including transpiration and evaporation), and withdrawal (wells, diversions) of water. Recent work by Carlson and Buffum (1989) indicates that remotely sensed data can be successfully integrated with ground-based meteorological data for estimating evapotranspiration on a regional basis. (E.4)

Soil Erosion. The form and rate of soil erosion are significant measures of changes in arid lands. Soil erosion will be measured by monitoring the form and density of drainage systems and the areal extent of bare soil with aerial and satellite imagery. A satellite-based laser altimeter for measuring surface profiles is currently under development by the National Aeronautics and Space Administration (NASA) and may provide the means to detect loss of material by erosion. (E.5)

Retrospective Indicators. The western United States contains a rich record of tree rings and fossil plant remains (pollen, charcoal, woodrat middens) documenting the response of plant communities to climatic change (e.g., Graybill 1985). By measuring both modern and ancient materials, a long-term record for these indices can be developed. With these retrospective data the rate of magnitude of future vegetation changes can be compared with the changes observable in a fossil record extending into the ice ages. (E.6, E.8-E.10)

Species Composition and Ecotone Location of Vegetation. This indicator will be used to detect changes in species composition, spatial distribution of various species, and species diversity. The location of plant assemblages in arid and semiarid regions responds dynamically and differentially to factors such as grazing and climate change. Both synoptic and reference site measurements will be used, in addition to data obtained from the retrospective indicator analysis. Variation in space and time will be measurable with this approach. (E.7)

Relative Abundance: Animals. The status of a community of organisms can sometimes be assessed by the status of a few species or categories of species that play critical roles. Birds could be used as indicators that integrate across resource classes; whereas small mammals, reptiles, and amphibians generally would serve to monitor conditions within a class. (G1.1)

Other Research Indicators

Abundance and Species Composition of Lichens and Cryptogamic Crusts. The abundance and species composition of lichens and cryptogamic crusts are sensitive to air pollution and mechanical disturbance. Cryptogamic crusts on arid soils control soil stability, nutrient status, and soil moisture dynamics (Harper and Marble 1988). (E.11)

Demographics: Animals. Population vigor is reflected in the recruitment of individuals into the breeding population and their subsequent survivorship. Parameters include age structure, sex ratio, fertility, mortality, survivorship, and dispersal; and such measurements are only appropriate for definite keystone species. (G1.2)

Morphological Asymmetry: Animals. The morphological variability in structures such as fins, teeth, and bones of bilaterally symmetrical organisms has been found to increase with exposure to chemical contaminants, hybridization, and inbreeding. This parameter would be an early-warning indicator of population-level responses to human-induced stressors. (G1.3)

7.2.1.2 *Exposure and Habitat Indicators for Arid Lands*

High-Priority Research Indicators

Exposure and habitat indicators are used by EMAP to identify and quantify changes in exposure and physical habitat that are associated with changes in response indicators. Eleven exposure and habitat indicators have been selected as research indicators for arid lands, nine of which are recognized as having high-priority status.

Foliar Chemistry. Nominal woodland, shrubland, or grassland condition depends on a sufficient supply and the proper balance of critical nutrients in foliage. Imbalances may signal imbalances in vegetation processes or indicate exposure to specific types of stresses. Also, the detection of certain foliar contaminants can provide information on possible mechanisms by which changes in vegetation condition might occur. (E.12)

Physiochemical Soil Factors. The chemical and physical properties of soil (pH and salinity profiles, carbon and nitrogen content, nutrient availability, structure and bulk density) have a direct impact on vegetation (Leonard et al. 1988). Hydrologic properties of soils (principally infiltration rate and hydrologic conductivity) can be altered by vegetation changes and mechanical disturbances (improper grazing, vehicular traffic, and fire). Decreased water-holding capacity and infiltration rates of soil can increase runoff, which frequently accelerates erosion. (E.13)

Exotic Plants. Introduced species are common in disturbed ecosystems. Although, in general, introduced species degrade the functioning and diversity of an area, their relative impacts among ecosystems are highly variable. (E.14)

Livestock Grazing. Grazing by cattle and sheep has had major impacts on as much as 40-80 million hectares (100-200 million acres) of land in the western United States (U.S. GAO 1988a). Grazing can alter species composition, impact riparian systems, and accelerate erosion (U.S. BLM 1978). The effects of grazing by domestic livestock, as well as wild and feral ungulates, must be accounted for when environmental impacts of other factors are assessed. This indicator will be measured by counting grazing animals on resource sampling units. (E.15)

Fire Regime. Fire is a natural phenomenon in most desert and grassland ecosystems, playing a crucial role in the release of nutrients and the creation of animal habitat. Environmental damage can occur, however, if fires occur too frequently or too infrequently. The extent and frequency of fires can be readily measured with remotely sensed data. (E.16)

Abundance and Density of Key Physical Features: Certain physical features of habitats (e.g., cliffs, outcrops, sinks, seeps, talus slopes) are critical to animal diversity and abundance. Land-use practices can alter the density and distribution of many key physical features. Many habitat features are specific to particular resource classes, but determining what to measure in a given class can be based on existing literature. (G3.1).

Mechanical Disturbance of Soils and Vegetation. Mechanical disturbances such as roads, trails, mines, disposal sites, and gravel extraction areas will fragment habitat, increase erosion, and promote the growth of exotic plant species (Webb and Wilshire 1983). Mechanical disturbance is readily measured by using remotely sensed data. (E.17)

Linear Classification and Physical Structure of Habitat. The distribution and disappearance of certain species is associated with critical features of their habitat. For example, overgrazing can result in the elimination of palatable plant species, soil compaction, and desertification. Species that depend on woodland, shrubland, or grassland habitat may not be able to survive in a habitat that is predominately unvegetated. Many studies have also demonstrated the relationship between animal diversity and vertical vegetation profile. (G3.2)

Landscape Pattern. Landscape indicators, calculated from data derived from remote sensing, describe the spatial distribution of physical, biological, and cultural features across a geographic area. These spatial patterns directly reflect the available habitat for animals, and they can be used to predict other functional attributes of arid ecosystems. (G3.3-G3.8)

Other Research Indicators

Biomarkers. A desirable feature of a monitoring program would be to detect an organism's response to human-induced stresses at the biochemical and cellular level before the stresses produce a detectable response at the organism and population levels. Although the use of biomarkers as early-warning response indicators requires more basic research, their present value for regional survey monitoring is to provide information to support or refute hypotheses on why ecological condition of arid lands is subnominal. (G2.1-G2.11)

Chemical Contaminants in Wood. Compounds of anthropogenic origin will be measured in woody plant tissue. By archiving samples we will have materials for analysis of contaminants in time series. (E.18)

7.2.2 Arid Land Indicators Not Selected for EMAP

Of the candidate indicators that were evaluated for arid lands, many did not rank high enough when judged against the EMAP indicator selection criteria (Table 7-1) to be proposed as research indicators. Some of the candidate indicators not selected, however, would be quite valuable at more intensive ecological research sites. Examples of candidate indicators and the main reason for their not being proposed as EMAP research indicators are listed below.

Microbial biomass in soils. Considered too variable, given the anticipated field sampling cycle of EMAP.

Historic photo analysis. Of high value as a retrospective indicator, but rejected because of cost considerations.

Plant litter decay rates. Discounted because it is not readily measured.

Seed production. Annual variability in response to temperature and precipitation variations make this indicator of questionable utility.

Plant pigments. This requires laboratory analysis for determination and is time-consuming. Remote sensing approaches for detecting changes in plant pigment concentrations (chlorophyll red edge shifts) are currently being tested and may provide valuable results in areas where green vegetation is dense enough to produce an adequate signal.

C, H, O isotopic ratios. This indicator may provide valuable information about the sources of plant carbon and plant water, but is not readily measured. Isotopic ratios would be an appropriate method for intensive studies.

Visual symptoms of foliar damage. Not considered sufficiently objective and quantifiable in arid resource classes.

Lignin/cellulose/chlorophyll/nitrogen ratios. Not considered cost-effective or readily interpretable.

Chlorophyll fluorescence. Not considered cost-effective or readily measured.

Cation distribution above water table: Not considered cost-effective because of arduous measurement procedures.

7.3 APPLICATION OF ARID LAND INDICATORS

One approach for determining subnominal condition in arid resource classes begins with estimating pristine conditions at each site, given the physical setting. Values of response indicators would likely be nominal for conditions that existed prior to the spread of introduced species or prior to prolonged grazing or water withdrawal. Obtaining such pristine values will not be widely possible, however, because of the lack of site-specific historical information regarding ecological condition in arid regions prior to human intervention. Where available, historic photo analysis can and has been successfully used in some arid systems; for example, the study of arid and semiarid regions by Hastings and Turner (1965) quantified species composition and mortality in a specific region by using this method.

A more realistic approach to determining subnominal conditions will be to use (1) reference sites and (2) response indicator values ascribed as subnominal. Response indicators values in regional reference sites with protected or (relatively) undisturbed settings can be used to provide examples of nominal conditions. Conversely, a series of indicator findings corresponding to degraded conditions will be used to identify subnominal threshold values. For example, sites with mechanical disturbances or infestations of noxious introduced species would be considered subnominal. All of this leads to the future development of integrated indices of ecological condition, with the scores or values in a number of indicators being used to calculate the indices.

7.4 RESEARCH NEEDS FOR EMAP-ARID LANDS

The highest priority for research indicators for arid lands is to develop a means for distinguishing whether subnominal conditions are a result of human-induced stress or a result of stress related to short-term climatic influences, such as annual fluctuations in temperature and precipitation. Some of the research indicators have been well tested, are likely to be applicable for EMAP, and can be readily implemented; others, however, will require additional development before they become routinely operational for EMAP. The development and use of retrospective indicators will be a key element for assessing near-term trends.

It is believed that many of these research indicators can be assessed by using airborne and satellite imagery. The cost-effectiveness of these remote sensing techniques can be enhanced by the development of automated procedures for data handling and analysis. Resource-class-specific expert systems should be investigated as a tool for assessing possible reasons for observed changes based on spectral signatures.

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SECTION 8

INDICATOR STRATEGY FOR AGROECOSYSTEMS

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8.1 INTRODUCTION

Agroecosystems provide the vast majority of the food consumed in the United States and continue to provide surplus food for export to other countries. Agroecosystems, the most intensively managed EMAP resource category, are typically located on some of the most productive land and cover nearly 30% of the earth's surface (Coleman and Hendrix 1988). Yield from U.S. agroecosystems is higher than from those in most other countries (Anonymous 1989). The extensive acreage devoted to crop and livestock production results from the single largest alteration of native habitat in North America in recent geological time (Jackson and Piper 1989). By design, agroecosystems are among the most intensively managed resources in the world (Pimentel and Dazhong 1990); because of the periodic and chronic disturbances created by agriculture, agroecosystems are also among the fastest changing of landscapes (Elliott and Cole 1989).

Agroecosystems are intensively monitored on a local, regional, and national level. Growers, agricultural extension agents, individuals in agribusiness, and economists regularly assess and report on the current status of crops and livestock production. Conditions that affect crop or livestock yields (e.g., poor soil quality or diseases) are usually corrected by management practices, such as applications of fertilizers or pesticides. Although agricultural systems may appear to be simple ecosystems, even annual monocultures can be ecologically complex (Coleman and Hendrix 1988; Paul and Robertson 1989). More effort needs to be devoted to monitoring their long-term sustainability and the condition of resources not directly associated with crop and livestock production.

Agroecosystems in EMAP are defined as lands managed for crop, pasture, and livestock production and the biotic and abiotic components of the underlying soils, surrounding transition zones (Carroll 1990), drainage networks, and adjacent areas that support natural vegetation and native animals. These areas form a unified whole consisting of food and fiber production, natural vegetation, and native animals, as presented conceptually in Figure 8-1.

Four EMAP-Agroecosystem resource classes were identified as agricultural production units with common management practices and common environmental problems: (1) field, vegetable, and forage crops; (2) fruit and nut crops; (3) managed pasture and nonconfined animal operations; and (4) confined animal feeding operations. Idle or natural areas within an agroecosystem will be assigned to their associated resource class; those areas remaining idle for a designated period and are of sufficient size will be reclassified according to their nonintensive resource categories (e.g., forests, arid lands).

The following sections provide a strategy that could be used to select and apply a proposed set of indicators for agroecosystems. We will specifically address the following items.

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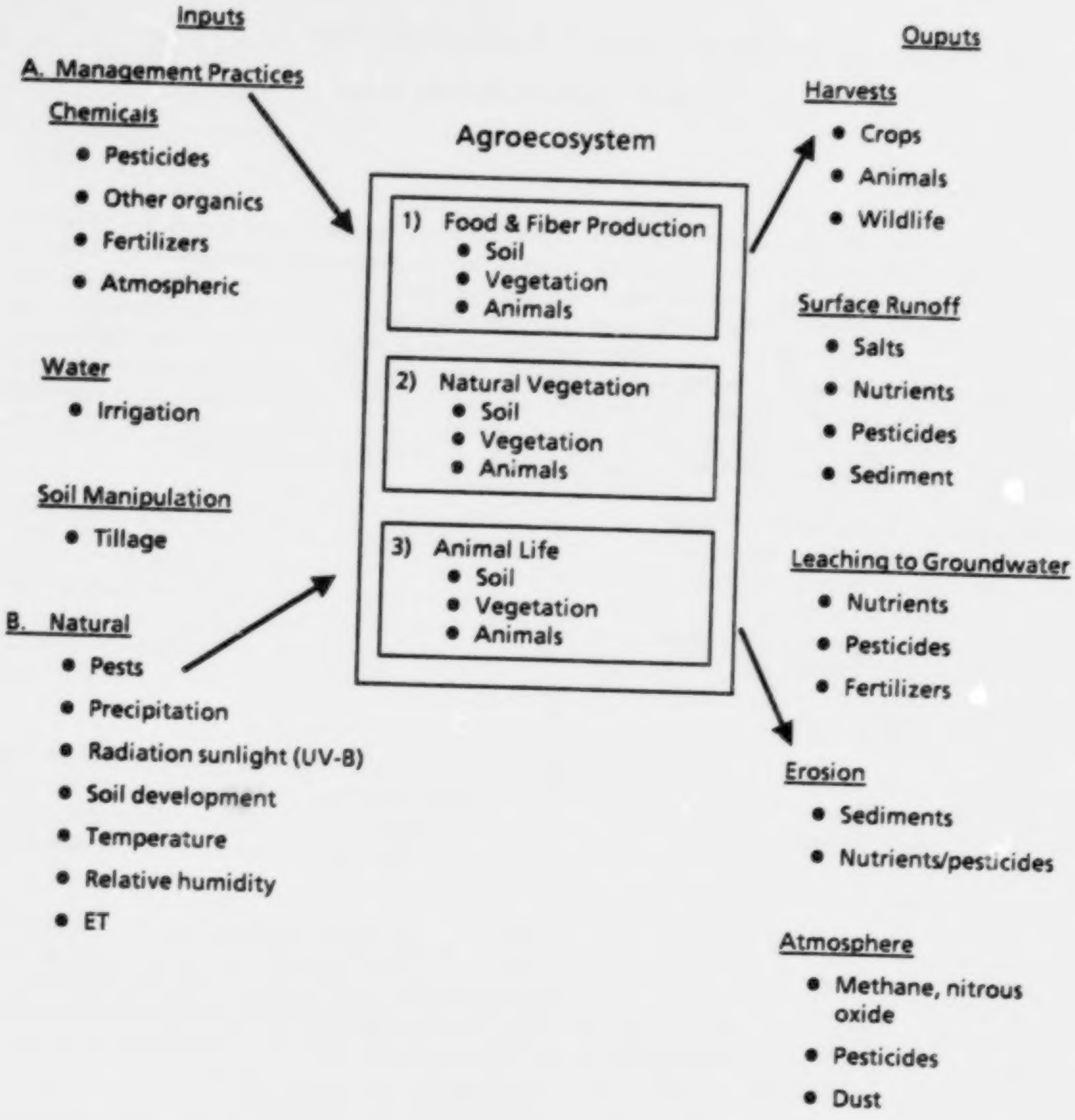

Figure 8-1. Conceptual model of agroecosystem.

- The public perception of the ecological condition in agroecosystems and associated environmental values
- A set of research indicators that define the ecological condition of agroecosystems
- How we might define subnominal condition in agroecosystems

8.2 IDENTIFICATION OF AGROECOSYSTEM INDICATORS

8.2.1 Perceptions of Agroecosystem Condition

Agroecosystems are essential for human welfare, cover vast acreage, provide habitat for natural vegetation and native animals in both managed and adjacent areas, and transport substantial amounts of residual exports to aquatic and terrestrial ecosystems. Income generated by agricultural products makes agriculture a leading sector of the U.S. economy. Agroecosystems also provide habitat and food for diverse biota and serve as important pathways for biogeochemical cycles. They are designed and managed to sustain high productivity through intensive development of improved crop plants and animals and through the application of chemicals and mechanical energy (Lowrance et al. 1984). Because of the importance of agriculture to societal well-being, public concern regarding status of and trends in ecological condition in agroecosystems is unquestioned. The time is ideal for initiating a long-term monitoring program of agroecosystems, because the emphasis in agricultural production is shifting from strict maximization to regeneration and optimization of resource utilization, while maintaining sustainability with minimum environmental damage (Elliott and Cole 1989).

The public is becoming increasingly concerned about the quality of food and water available for consumption as well as the health of the overall biosphere (Buttel 1990; Soule et al. 1990). Use of pesticides and other agricultural chemicals has become routine. This dependence, however, makes agriculture the largest contributor of nonpoint-source pollutant loadings for streams and lakes in the United States (Anonymous 1989; Levins and Vandermeer 1990; Soule et al. 1990). The public perception is thus one of concern for food and water quality and environmental health, confounded with a strong desire to have an abundant supply of inexpensive food and fiber products (Buttel 1990).

8.2.2 Environmental Values for Agroecosystems

What constitutes a "healthy" agroecosystem cannot be determined a *priori*. Instead, the perception of health is based on knowledge of an acceptable range of values for measures related to specific components of agroecosystems. In screening indicators for EMAP, both public and scientific concerns were translated into environmental values that could be assessed directly through the measurements of one or several indicators (Figure 2-1).

Several pertinent scientific, social, economic, and environmental issues are associated with agricultural crop and animal production systems and their surroundings. These issues can be essentially summarized by environmental values: productivity and sustainability, biodiversity, and freedom from contamination.

Productivity and sustainability refer to the capacity of a particular agroecosystem to maintain an economically acceptable level of crop or livestock productivity over time. A primary objective of agroecosystem managers is to obtain maximum productivity with a minimum of external inputs. Potential decreases in system sustainability can be masked in the short term by management practices and increased inputs. The time scale of public concern for sustainability, however, is decades or centuries, not a single crop-growing season.

Although linked to sustainability, biodiversity refers to the ability of a highly managed ecosystem to support species that do not contribute directly to crop and livestock production. Such species include important game and unmanaged animal life, controllers of pollination and insect pests, songbirds, and wildflowers.

Contamination of food and resources is an issue of growing public concern, especially as it affects the productivity, structure, or function of an agroecosystem. Human-induced stressors of contamination include atmospheric deposition, point sources into potential irrigation water, agricultural chemicals, agricultural wastes, and some biological technologies. Specific types of contamination include pesticides, antibiotics or residues in food, and other agricultural wastes; salinization of soils; and the presence of exotic pests.

8.2.3 Agroecosystem Indicators Appropriate for EMAP

Two EMAP workshops were held in Raleigh, North Carolina, in August 1989 to discuss candidate indicators of agroecosystem health, structure, and function. Each participant (see Appendix I) was asked to develop a list of possible indicators, related to his or her area of expertise. From these workshops, 130 candidate indicators were proposed. After candidate indicators were summarized and examined for redundancy, 90 specific indicators were considered, from which a refined candidate indicator list for further examination was developed.

An extended fact sheet was prepared for each indicator for incorporation into this report. Further critical examination of each indicator was performed by one or more members of EMAP-Agroecosystems and the results were presented at an indicator strategy workshop in Idaho Falls, Idaho, in May 1990. A written external review of these indicators also was performed in April 1990 (Appendix I.8), followed by a review by the EPA Science Advisory Board in May 1990. Candidate indicators were again considered in extensive, critical discussions, which included an evaluation based on the EMAP indicator selection criteria (Table 8-1). The final list of research indicators was prioritized, and needed measurements were identified. Specific information needed from demonstration studies in order to further evaluate research indicators was also identified.

Figure 8-2 provides an overview of the proposed EMAP-Agroecosystems indicators strategy, and Table 8-2 identifies the specific environmental values addressed by each indicator. A brief description of each research indicator is given here. More detailed descriptions of the indicators, their application, suitable index period, variability, and research needs are listed in Appendices F and G, as referenced by the code in parentheses at the end of each description below.

8.2.3.1 *Response Indicators for Agroecosystems*

Response indicators are used by EMAP to quantify and classify the condition of ecological resource classes. Ten response indicators have been selected as research indicators for agroecosystems, eight of which are recognized as having high-priority status.

High-Priority Research Indicators

Nutrient Budgets. The cyclic processing of chemical elements within an ecosystem is fundamental to the maintenance of the system. Nutrient concentrations in soil and organisms and nutrient leaching from soil will be measured. Major changes in these concentrations can provide an early warning of agroecosystem response to stress. (F.1)

Soil Erosion. Loss of soil due to erosion depletes the productivity of the land. As the more productive surface layer is lost, less fertile soil layers are incorporated into the plow layer. Erosion on farmland also results in the entry of sediments and chemicals into surface waters. Nominal or subnominal status and long-term trends in soil erosion can be evaluated in terms of site tolerance (effect on productivity) to soil loss, as classified by the Soil Conservation Service. (F.2)

Microbial Biomass in Soils. Soil microorganisms play a vital role in the retention and release of nutrients and energy in agricultural soils, and they are sensitive to environmental hazards. (F.3)

Land Use/Extent of Noncrop Vegetation. Information on land use (cropland, pasture, set aside, abandoned, woodlot) will indicate trends in crop preferences and grower perceptions concerning market opportunities, profitability, and sustainability of production. The relative areal extent of crop and noncrop vegetation on arable lands can reflect agroecosystem condition. Land use can be related to other indicators such as the index of soil productivity, agricultural pest density, and quality of irrigation waters. (F.4)

Table 8-1. Evaluation of Some Candidate Indicators for Agroecosystems by EMAP Selection Criteria (H = High, M = Medium, L = Low)

	Critical					Desirable						
Candidate Indicator	Correlate Unmeasured[1]	Regional Application[2]	Integrate Effects[3]	Relate Monotonic[4]	Simple Quantification[5]	Important[6]	Responsive[7]	Anticipatory[8]	Standard Method[9]	Low Measure Error[10]	Historical Data Base[11]	Cost Effective[12]
Selected as Research Indicators												
Nutrient Budgets	H	M	M	M	L	H	M	M	M	L	M	L
Soil Erosion	H	H	H	H	M	H	H	H	H	M	H	H
Microbial Biomass: Soils	M	L	H	L	L	H	H	M	M	L	L	L
Land Use/Extent of Non-Crop Vegetation	H	H	H	H	H	H	H	H	H	H	H	H
Crop Yield	H	H	H	H	M	H	H	L	H	H	H	H
Livestock Production	H	M	H	H	M	H	H	L	H	H	M	M
Visual Symptoms of Foliar Damage: Crops	H	H	H	H	L	H	H	M	M	M	L	M
Agric. Pest Density	H	H	H	M	L	H	H M	L	H	M	L	M
Lichens/Mosses Clover/Earthworm Bioassays	H M	H M	H M	M	L	H	H M	H	M	M L	L	L
Quantity/Quality of Irrigation Waters	M	M	H M	M	M	H	M	H	M	M	L M	M
Soil Productivity Index	H	H	H	M	L	H	H	H	M	M	M	M
Considered But Not Selected												
Chlorophyll Concentration in Vegetation	M	L	M	L	H	M	M	M	M	M L	L	M
Eggshell Quality	M	M	M	M	L	M	M H	H	M	M	M	L
Aquaculture Production	H	L	H	M	L	H	M H	L	H	M H	L M	M
Blood Serum Chemistry: Native Animals	M	L	M	M	L	M H	M	M	L	L	L M	L
Leaf Surface Microflora	M	L	M	L	L	M	M	L	M	L	L	L
Leaf Water Content	L	L	M	L	M	M	M	L	H	H M	M	M

1 Correlates with changes in processes or other unmeasured components.
2 Applies to a broad range of regional ecosystem classes.
3 Integrates effects over time and space.
4 Relates unambiguously and monotonically to an endpoint, a relevant exposure or habitat variable.
5 Can be quantified by synoptic monitoring or by automated monitoring in a cost effective manner.
6 Is important to the overall structure and function of ecosystems.
7 Responds to stressors of concern or management strategies.
8 Is anticipatory by providing an early warning to widespread changes.
9 Has a standard method of measurement.
12 Exhibits low measurement error.
11 Has a historical data base or the capability of being generated from accessible data sources.
12 Is cost effective (has low cost and high information value).

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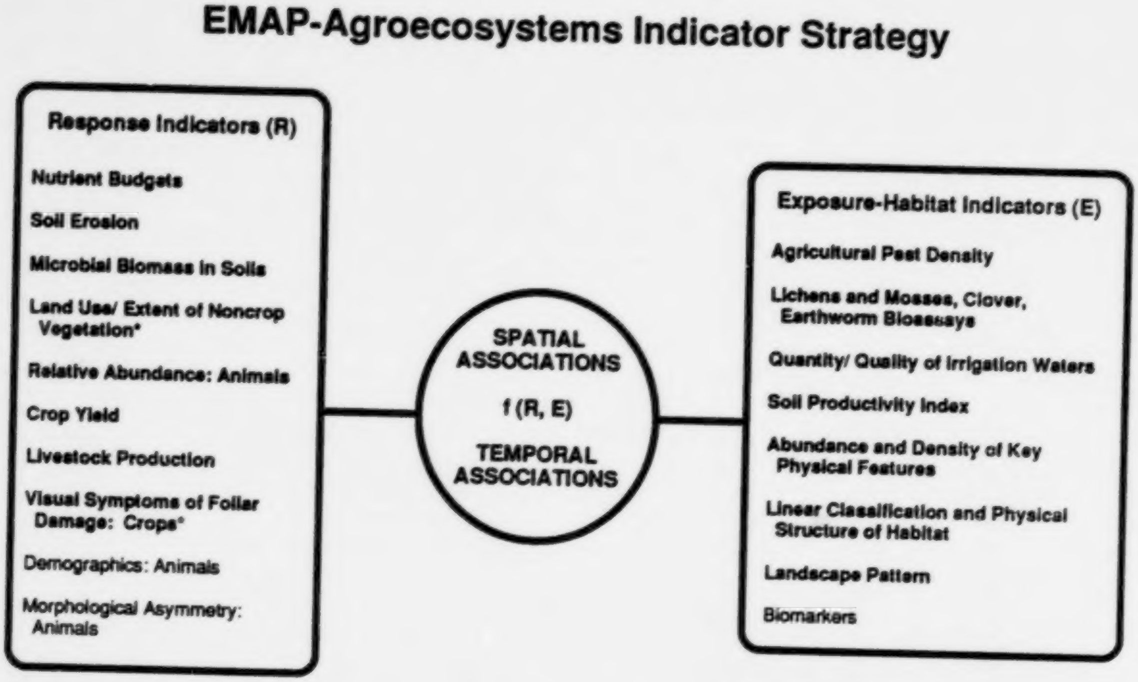
EMAP-Agroecosystems Indicator Strategy
Response Indicators (R)
Nutrient Budgets
Soil Erosion
Microbial Biomass in Soils
Land Use/ Extent of Noncrop Vegetation*
Relative Abundance: Animals
Crop Yield
Livestock Production
Visual Symptoms of Foliar Damage: Crops*
Demographics: Animals
Morphological Asymmetry: Animals
SPATIAL ASSOCIATIONS
f (R, E)
TEMPORAL ASSOCIATIONS
Exposure-Habitat Indicators (E)
Agricultural Pest Density
Lichens and Mosses, Clover, Earthworm Bioassays
Quantity/ Quality of Irrigation Waters
Soil Productivity Index
Abundance and Density of Key Physical Features
Linear Classification and Physical Structure of Habitat
Landscape Pattern
Biomarkers

Figure 8-2. Diagram of the proposed EMAP-Agroecosystems Indicator Strategy. Indicators in bold lettering are high-priority research indicators. Response indicators with an asterisk (*) also function as exposure and habitat indicators.

Table 8-2. Environmental Values Addressed by High-Priority Research Indicators for an Agroecosystem

	Environmental Value		
High-Priority Research Indicator	Sustainability of crop resources	Contamination	Integrity of noncrop resources
Nutrient budgets	X		
Soil erosion	X		
Microbial biomass in soils	X	X	
Land use/Extent of noncrop veg.	X		X
Relative abundance: animals			
Crop yield	X		
Livestock production		X	X
Foliar damage		X	
Pest density	X		
Bioassays		X	X
Irrigation water quantity	X		
Irrigation water quality	X	X	
Soil productivity	X		
Habitat and landscape descriptors			X

Relative Abundance: Animals. The status of a community of organisms can sometimes be assessed by the status of a few species or categories of species that play critical roles. Some types of birds could be used as indicators that integrate across resource classes, whereas small mammals, reptiles, and amphibians generally would be used to monitor condition within a resource class. (G1.1)

Crop Yield. Crop yield integrates the action of a large array of biotic and abiotic factors that affect crop growth. Yield for a given crop, determined at crop maturity, can be compared with established standards in a specific area. Crop yield related to given inputs, such as amount of fertilizer, also provides an index of production efficiency. (F.5)

Livestock production. The production of beef, pork, poultry, and fish for human consumption; horses; and other nonfood animals is a vital function of agroecosystems. Responses of livestock to a large array of biotic and abiotic factors can be synthesized into measures of production efficiency and overall productivity. Waste output from confined feeding operations also provides the potential for resource contamination and should be monitored. (F.6)

Visual Symptoms of Foliar Damage: Crops. Crop condition is often determined by the presence or absence of visible symptoms caused by plant pests (such as pathogens or insects), pollutants, nutrient imbalance, pesticide toxicity, or weather extremes. Environmental data (weather, types and concentrations of pollutants), pest density, soil and chemical inputs can be related to specific foliar symptoms. (F.7)

Other Research Indicators

Demographics: Animals. Population vigor is reflected in the recruitment of individuals into the breeding population and their subsequent survivorship. Parameters include age structure, sex ratio, fertility, mortality, survivorship, and dispersal; and such measurements are appropriate only for definite keystone species. (G1.2)

Morphological Asymmetry: Animals. The morphological variability in structures such as teeth and bones of bilaterally symmetrical organisms has been found to increase with exposure to chemical contaminants, hybridization, and inbreeding. This parameter would be an early-warning indicator of population-level responses to man-made stressors. (G1.3)

8.2.3.2 *Exposure and Habitat Indicators for Agroecosystems*

Exposure and habitat indicators are used by EMAP to identify and quantify changes in exposure and physical habitat that are associated with changes in response indicators. Ten exposure and habitat indicators have been selected as research indicators for agroecosystems, nine of which are recognized as having high-priority status.

High-Priority Research Indicators

Visual Symptoms of Foliar Damage: Crops. Environmental data (weather, types and concentrations of pollutants), pest density, soil and chemical inputs can be related to specific foliar symptoms. (F.7)

Agricultural Pest Density. Density of pests, such as insects, pathogens, and weeds, is an indicator of the degree of biological stress to which crop plants are exposed. Species diversity and frequency of plant-parasitic nematodes and weeds are relatively easy to measure (i.e., extent of weeds, presence of nematodes in soil samples). (F.8)

Lichens and Mosses, Clover, Earthworm Bioassays. Lichens or mosses, higher plants such as white clover, and animals such as earthworms can serve as biomonitors for a variety of hazards. Known responses of these species to specific stressors such as air pollutants and a knowledge of the relationships between bioassay species and crop or noncrop plant responses would enable a quantification of such stresses as a plausible explanation for subnominal agroecosystem condition. (F.9)

Quantity and Quality of Irrigation Waters. The quality of surface water and ground water impacts productivity, sustainability, and condition (health) of plants and animals in the agroecosystem. Quantity of water available for use in agroecosystems may also serve as an indication of sustainability of farming practices. The use of surveys would require that indices be used to represent annual or seasonal averages. (F.10)

Soil Productivity Index. Each soil has a productivity capacity for a specific crop or sequence of crops under a defined set of management practices. Maintaining soil productivity depends on using best management practices, the characteristics of the site, and the biotic and abiotic stresses applied to the system. A change in soil productivity over time indicates a shift in sustainability of the system. Important metrics that would be considered in this index include soil rooting depth, topsoil thickness, available water capacity, texture, bulk density, permeability, clay fraction, pH, and soil organic matter content. (F.11)

Land Use and Extent of Noncrop Vegetation: In addition to serving as a response indicator, land use and extent of noncrop vegetation also can influence the abundance and species composition of native animals. (F.4)

Abundance and Density of Key Physical Features: Certain physical features of habitats (e.g., cliffs, outcrops, sinks, seeps, talus slopes) are critical to animal diversity and abundance. Land-use practices can alter the density and distribution of many key physical features. Many habitat features are specific to particular resource classes, but determining what to measure in a given class can be based on existing literature. (G3.1)

Linear Classification and Physical Structure of Habitat. A large proportion of the managed landscape in the United States is composed of patches of natural vegetation within a matrix of different agroecosystems. The habitat layer index, derived from a combination of aerial photograph interpretation and field validation, appears to be an appropriate indicator for evaluating habitat (vegetative community) structure. Habitat structure can be used to interpret potential suitability of an area for occupancy, foraging, and breeding activities of animal life. (G3.2)

Landscape Pattern. Landscape indicators, calculated from data derived from remote sensing, describe the spatial distribution of physical, biological, and cultural features across a geographic area. These spatial patterns directly reflect the available habitat for animals as well as predict other functional attributes of agroecosystems. (G3.3-G3.8)

Other Research Indicators

Biomarkers. A desirable feature of a monitoring program would be to detect an organism's response to human-induced stresses at the biochemical and cellular level before the stresses produce a detectable response at the organism and population levels. Although the use of biomarkers as early-warning response indicators requires more basic research, their present value for regional survey monitoring is to provide information to support or refute hypotheses on why ecological condition of agroecosystems is subnominal. (G2.1-G2.11)

8.2.4 Agroecosystem Indicators not Appropriate for EMAP

Among the initial list of candidate indicators, many were excluded because they are in very early stages of development. For example, there is evidence that assays of leaf surface microflora can indicate the presence of adverse biochemical substances or an excess of specific types of radiation; analysis of animal hair or bird feathers shows promise for detecting the presence of pesticides. Although many of these indicators would be appropriate for the examination of specific cause-effect relationships within agroecosystems, they are not considered appropriate at this time for examining agroecosystem condition in a regional or national monitoring system.

Several candidate indicators were not selected for further consideration because continuous monitoring, which is inconsistent with EMAP's survey monitoring design, is needed. For example, chlorophyll content in leaves changes in response to phenologic, physiologic, and environmental conditions (Tucker et al. 1981); therefore, meaningful interpretations of chlorophyll data gained from measurement techniques, such as use of satellite remote sensing, would require weekly or monthly observations during the growing period. Indicators such as water content in foliage and populations of soil bacteria were excluded because their large spatial and temporal variabilities would preclude meaningful interpretations within the EMAP context.

8.3 APPLICATION OF AGROECOSYSTEM INDICATORS

Assessing the "health" of any ecological resource is challenging. The fact that biotic populations and ecosystems are dynamic creates problems in defining threshold values for response indicators to determine subnominal condition. Such difficulties are compounded for agroecosystems because these ecosystems are created and maintained by man and are intentionally and continuously perturbed for the production of market commodities.

The response indicators described in Section 8.2.3 (e.g., nutrient budgets, crop yields, livestock production, soil microbial biomass, and visual symptoms of foliage to crops) would be used initially to determine the proportion of agroecosystems that are subnominal. The exposure and habitat indicators (e.g., agricultural pest density, bioassays, quantity and quality of irrigation waters, soil productivity index, and land use or extent of noncrop vegetation) would be used to look for plausible associations between exposure or physical habitat and ecological condition. Nominal means that "the values of indicators measured on the resource indicate that it is exhibiting structural and functional attributes typical of resources that are experiencing little or no stress." For agroecosystems, this definition is expanded to include the concept that a nominal agroecosystem has the structural and functional attributes of resources that experience little or no stress except for those stresses intentionally and continuously placed on it by man for efficient crop and livestock production. The potential for continuous change in agroecosystems or for growers to actively respond to situations or conditions that would cause a resource sampling unit to be classified as subnominal (e.g., native vegetation decline due to fungicide applications) complicates the definition of what constitutes subnominal condition.

Three basic approaches, as detailed in Section 2.3.3, are available for setting subnominal threshold values - the use of existing numeric criteria, reference sites, and classification. In agroecosystems, the use of numeric criteria, which are based on external conditions such as management targets or yield projections, are appropriate for an agronomic view. If production or a yield target is the primary criterion of interest, then from an agronomic view, the agroecosystem is nominal if production targets (which may be long-term average yields) are met. Such a view, however, is not appropriate for EMAP, because its major goal is to monitor ecological condition, not short-term productivity or economic return.

The second approach would be to survey regional reference sites and develop a reference population for each response indicator. Using this approach, the reference population for agroecosystems could be sites or grower operations that employ best management practices for the given crops, livestock, and types of adjacent areas being considered. This approach has several advantages for agroecosystems. Reference populations could be established regionally and, with proper documentation, future determinations of resource sampling units as nominal or subnominal would be possible on the basis of new or changing criteria obtained from the reference sites. While it would be quite difficult to establish regional reference sites that are not exposed to regional air pollutants, the use of exposure indicators such as the white clover bioassay (see indicator F.9) could, however, enable calibration or standardization of pollutant effects among regional reference sites.

The third approach, classification of sites using a multivariate index, would rely totally on data from the EMAP probability sample of the target resource population. No such "index of agroecosystem health" currently exists to facilitate the identification of a subnominal threshold. However, this approach might eventually represent the best blend of the agronomic and ecological approaches to determining agroecosystem condition.

The detailed approach for establishing the subnominal thresholds for specific response indicators and specific agroecosystem resource classes remains to be formulated. A combination of the possible approaches, particularly regional reference sites and classification, may be the best solution to the problem.

8.4 RESEARCH PRIORITIES FOR AGROECOSYSTEMS

A three-stage indicator evaluation project is proposed, which follows the EMAP indicator evaluation framework (Figure 2-7) and would be implemented in cooperation with the U.S. Department of Agriculture (USDA) National Agricultural Statistical Service and the USDA Agricultural Research Service. The project would evaluate the proposed research indicators, establish and evaluate specific criteria and decision rules for determining ecological condition, specify the logistics of data collection to support chosen indicators, and develop the most effective ways to report data on individual indicators and on indices.

The first stage of the evaluation project would establish for each research indicator its (1) range of possible, likely, and desirable values; (2) spatial and temporal variability of values in resource sampling units; (3) reliability and information content; (4) usefulness or sensitivity in determining ecological condition; and (5) appropriate critical index period or periods. Further, in stage 1 the three approaches for establishing the subnominal threshold for response indicators would be critically examined, and one or more specific strategies for threshold establishment would be developed.

In the second stage of the proposed evaluation project, a limited geographical area would be sampled, and specific indicator data would be collected. Based on the results of stage 2, field-implementation protocols for each indicator would be finalized, and an analysis of cost-effectiveness for each indicator that appears suitable and appropriate would be conducted. At the same time, the actual values of the subnominal thresholds would be established and evaluated for regional and national appropriateness for the purposes of EMAP. The specific strategies for establishing the subnominal threshold also would be compared. From the overall analysis of indicators and threshold establishment strategies, a provisional index of agroecosystem condition would be developed and evaluated for sensitivity, efficiency, reliability, and appropriateness. Those research indicators that pass the first two stages of testing would be identified as developmental indicators (see Figure 2-7).

In the third and final stage of the evaluation project, the developmental indicators would be sampled throughout a region. Final evaluation of developmental indicators and criteria for establishing the subnominal threshold would be performed. Based on results of stage 3, multiregional or national plans for implementing and reporting the core indicators for the EMAP agroecosystem resource category would be developed.

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SECTION 9

INDICATORS RELEVANT TO MULTIPLE RESOURCE CATEGORIES

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L.R. Shugart[1], and R.V. O'Neill[1]

9.1 INTRODUCTION

For practical purposes EMAP has focused initially on six ecological resource categories; however, in reality these are components of the "whole" ecosystem, or biosphere. Indicators that apply to several or all EMAP resource categories will allow comparison of ecological condition both within and among categories. Animal indicators, biomarkers, and landscape indices are examples of such indicators and are discussed in this section and Appendix G.

Animal indicators, biomarkers, and landscape indicators are addressed in this section because they are EMAP resource categories. Eventually, the indicator strategy for each resource category (Sections 3 through 8) will incorporate these indicator types. Some animal indicators are already proposed for the individual resource categories. Most, however, are discussed as a group in this section for ease of presentation and because the strategy for monitoring these indicators in EMAP is not fully developed at this time.

Stressor indicators are also relevant to all resource categories and, like the three types of indicators already mention, the strategy for their inclusion in EMAP currently is not well defined. For these reasons, this section also addresses stressor indicators. The use of stressor indicators will depend on the availability of consistent external (off-frame) data sets for large geographic regions and their data quality. The same stressor indicators will be useful for several EMAP resource categories and are discussed only briefly in this report.

Landscape indicators should be useful as habitat indicators for most EMAP terrestrial resource categories, and their application to aquatic systems resource categories will be as stressor indicators. Landscape indices have been used to model the spread of disturbances such as fire and the movement of wildlife (Turner et al. 1989; O'Neill et al. 1988b). In addition, indicators of landscape pattern and habitat structure will probably be used to indicate the potential for certain animals to be present in an area, as well as to identify areas for further evaluation of animal condition. The extent to which EMAP can monitor terrestrial animals has not yet been determined. From an efficiency standpoint, it would be ideal to gather data on animals that are also used for biomarker measurements. Although biomarkers may eventually serve as valuable indicators for defining animal health at the regional scale, they are collectively considered research indicators at this time.

The identification of EMAP indicators relevant to many resource categories was done by a small group of experts within input from various EMAP workshops and resource groups. Contributors and workshop participants are listed in Appendix I.

9.2 ANIMAL INDICATORS

Monitoring animal indicators is necessary for determining ecological condition of EMAP resource classes. Animals are often endpoints in ecological assessments, because the public is very interested in the well being of animal populations. In addition, animals can be monitored at various spatial scales, and they are part of all ecosystems. Appropriate EMAP indicators for animals (Table 9-1) focus on attributes of ecosystem structure (habitat indicators such as landscape and habitat vertical structure) and composition (response indicators such as relative abundance of select species). For simplicity, "animals" is used in this discussion to include birds, reptiles, amphibians, mammals, fish and other aquatic organisms, and selected invertebrates (e.g., bees, butterflies, and snails). Section 9.2 focuses on terrestrial animals and amphibians (organisms that require both terrestrial and aquatic environments). Aquatic organisms are addressed in Sections 3 and 4.

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Indicators that quantify the health of animal populations and communities are needed for EMAP. It has sometimes been assumed that monitoring habitat variables obviates the need to monitor animals directly; however, the presence of suitable habitat does not guarantee that the species of interest are present. Population density can vary tremendously because of biotic factors while habitat-carrying capacity remains roughly constant (Schamberger 1988). Conversely, inferences based solely on biotic variables such as animal population density can be misleading. Among vertebrates, for example, socially subordinate individuals may

Table 9-1. Research Indicators Applying to Multiple Resource Categories[a]

RESPONSE INDICATORS

Animal Life
Relative Abundance: Animals
Demographics: Animals
Morphological Asymmetry: Animals

EXPOSURE AND HABITAT INDICATORS

Biomarkers
DNA Alteration: Adduct, Secondary Modification, Irreversible Event
Cholinesterase Levels
Metabolites of Xenobiotic Chemicals
Porphyrin Accumulation
Histopathologic Alterations
Macrophage Phagocytotic Activity0
Blood Chemistry Assays
Cytochrome P-450 Monooxygenase System
Enzyme-Altered Foci

Habitat
Abundance or Density of Key Physical Features
Linear Classification and Physical Structure of Habitat

Landscape
Habitat Proportions
Patch Size and Perimeter-to-Area Ratio
Fractal Dimension
Contagion or Habitat Patchiness
Gamma Index of Network Connectivity
Patton's Diversity Index

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[a] Indicators in bold lettering are high-priority research indicators.

occur in areas of marginal habitat (Van Horne 1983). Also, exotic species may displace residents and, in turn, affect ecological processes. Thus, monitoring both habitat and animal variables is necessary in most cases.

Although states and federal resource agencies collect large amounts of wildlife data, no standardized national or regional inventory exists that permits a consistent summarization of wildlife and fish resources, even for big game populations which have received the most attention. Few data are available for assessing the status of nongame and small game populations over large regions (Flather and Hoekstra 1989). Breeding birds are the only animals for which comparative data are available on a continental scale (Robbins et al. 1986). Even if EMAP monitors only a few animal indicators, the program will begin to help fill a void in our knowledge of regional ecological condition. Of course, for migratory species, diagnosing trends in animal indicators will always be complicated. The challenge for EMAP is to select measurable indicators of animals at multiple levels of biological organization - regional/landscape, community/ecosystem, and population/species.

9.2.1 Identification and Application of Animal Indicators for EMAP

The monitoring survey design of EMAP poses a challenge for monitoring animals. An EMAP-sponsored workshop of experts on monitoring animals (see Appendix I) was held in March 1990 to identify appropriate animal indicators for EMAP. The only animal response indicator suggested for high-priority research status was the relative abundance, when feasible, or presence/absence of selected species. The simplest metric, presence/absence, is the most likely for EMAP, even though relative abundance measurements yield more information on community composition and are more desirable. Habitat structure (vertical and horizontal) and several landscape indices are high-priority habitat indicators for animals. Animal types were rated on how well they satisfied the EMAP indicator selection criteria (Table 9-2). These animal types were also evaluated with regard to their value as indicators for inland surface waters, wetlands, forests, arid lands, and agroecosystems (Table 9-3). Eventually, one or more animal types will be selected for monitoring within an EMAP resource category. Use of the same animal indicators across resource classes or even categories, while not necessary, would aid integrated assessment efforts.

If animals are trapped during monitoring, serious consideration should be given to sampling certain biomarkers (Section 9.3) from captured animals. A suite of biomarkers could be measured from ubiquitous animals such as deer mice and leopard frogs to provide a baseline for these indicators across resource classes and even categories. Biomarkers of sensitive species or species specific to certain conditions could also be monitored. Establishing one or more intensive animal monitoring sites (reference sites) that are representative for each EMAP resource class will be important for the development of animal indicators. Ideally, these sites would be located at existing long-term research sites such as the National Science Foundation's Long-Term Ecological Research Sites (LTERs), Biosphere Reserves, or the 20-year sites of the U.S. Fish and Wildlife Service (FWS). Data from intensive monitoring sites can help define indicator variability from natural causes, be used to improve monitoring designs, and serve as important checks on the temporal and spatial scales being monitored by the extensive EMAP sampling design.

9.2.1.1 *Birds*

Because field sampling methods for animals are often resource intensive, EMAP must make maximum use of existing regional and national programs that monitor animals, as well as long-term intensive sampling sites such as LTERs and Biosphere Reserves. Birds are one of the few animals for which consistent, historical data sets exist on regional and national scales: the North American Breeding Bird Survey (BBS), the Christmas Bird Count (CBC), and the Breeding Bird Census (Eagles 1981; Verner 1985). The Manoment Bird Observatory coordinates the International Shorebird Survey during autumn migration, and the FWS surveys waterfowl by airplane during the breeding season and winter. Birds may also be the one animal type that is a useful response indicator in most resource categories (Table 9-3). The point count or Indexes Ponctuels d'Abondance method using a fixed 10-min time period for counts at a field sampling unit is considered appropriate for monitoring birds in EMAP. The method is a means of obtaining indices of abundance for

Table 9-2. Capability of Various Animal Types to Satisfy EMAP Indicator Selection Criteria[a]

Criteria for Indicator Selection	Vertebrates					Invertebrates						
	Mammals											
	Small	Large	Reptiles	Amphibians	Birds	Grass-hoppers	Ground-Dwelling Beetles	Butter-flies	Bees	Ants	Termites	Snails
Respond to long-term stressors such as climate change (decades)	H	L	M	H	H	M	H	M	L	M	H	H
Respond to immediate stressors (months to years)	M	H	L	H	H	M	H	H	M	M	M	H
Apply to several ecosystems	H	L	L	H	H	H	H	M	H	H	M	L
Integrate effects over time and space	L	H	L	L	L	M	L	L	L	M	M	L
Magnitude of year-to-year variability (signal-to-noise ratio)	L	L	M	M	M	L	M	L	L	H	H	M
Standard methodology available (repeatable)	H	L	M	L	H	H	H	H	M	L	H	M
Degree of measurement error	M	L	M	L	M	L	M	L	L	L	L	M
Cost-effective	L	L	M	L	M	H	L	H	M	L	M	M
Existing data bases available	H	H	H	M	H	H	H	H	M	M	L	L
Can be monitored by remote sensing	L	L	L	L	L	L	L	L	L	L	L	L
Short generation time (high vagility)	H	M	L	L	H	M	L	M	L	L	L	L
Sampling qualities (nondestructive)	H	H	M	L	H	H	M	H	H	L	L	L
Public relations value	L	H	L	L	H	L	L	H	M	L	L	L

[a] H = high; M = medium; L = low.

Table 9-3. Relative Usefulness of Animal Types as Indicators Within Ecological Resource Categories[a]

	Inland Waters	Wetlands	Forests		Arid Lands				Agroeco-systems
			Coniferous	Deciduous	Tundra	Deserts	Scrub	Grasslands	
VERTEBRATES									
Small Mammals	no	M	M	M	H	H	M	H	H
Reptiles									
Lizards	no	no	L	L[b]	no	H	M	H	L
Turtles and Tortoises	H	H	-	-	-	H	-	-	-
Amphibians									
Frogs and Toads	H	H	L	M	no	L	L	L	L
Salamanders	H	H	H	H	no	L	L	L	L
Birds	H	M	H	H	H	L	M	H	M
INVERTEBRATES									
Grasshoppers	no	M	L	L	M	H	M	H	H
Ground-Dwelling Beetles	L	M	H	H	M	M[c]	M	H	L
Butterflies	no	L	L	L	L	M	H	M	L
Bees	no	?	L	M	H	M	M	M	H
Ants	no	no	M	H	L	H	H	M	L
Termites	no	no	L	M	no	H	M	H	no
Snails and Slugs	H	H	M[d]	H	L	L[e]	M	M	L

[a] H = high; M = medium; L = low. Bold letters indicate the most useful animal groups within a resource category; animal indicators for Near Coastal were not ranked.
[b] High in Southwest.
[c] High in Great Basin.
[d] High in Northwest.
[e] Medium in Chihuahuan Desert.

comparing bird populations of different habitats (or of the same habitat in different locations) during the breeding season (Ryder 1986). Because of low detectability, the monitoring of some species such as marsh birds (Gibbs and Melvin 1989) or woodland raptors (Fuller and Mosher 1981) may require a specialized technique such as playback of vocalizations.

The BBS is an ongoing program sponsored jointly by the FWS and the Canadian Wildlife Service. Its main purpose is to estimate population trends of the many bird species that nest in North America north of Mexico and that migrate across international boundaries. The survey provides information, both locally (by ecological or political regions) and on a continental scale. Information includes (1) short-term population changes that can be correlated with specific weather incidents, (2) recovery periods following catastrophic declines, (3) normal year-to-year variations, (4) long-term population trends, and (5) invasions of exotic species (Robbins et al. 1986). The BBS surveys 500 bird species by using 2000 random roadside routes that are stratified by physiographic region (Bystrak 1981).

The CBC is the best known and probably most used source of information on geographical distribution of nongame birds in winter. Counts are made in more than 1500 circles of 24-km (15-mi) diameter. The most meaningful data are expressed in number of birds observed per party-hour. Scientific studies have worked with CBC data (Butcher 1990; Bock and Root 1981), and popular evaluations of the CBC have been written by Bock (1979), Robbins (1966), and Wing and Jenks (1939). Both the BBS and CBC are biased toward birds that occur near roads and rely on volunteers (Faanes and Bystrak 1981), so data quality may be an issue for EMAP. However, such monitoring programs are excellent examples of how EMAP could use animal indicator data from external sources. Birds will be important animal indicators because of their applicability to several resource categories, extensive historical data sets, knowledge of ecological requirements, standardized monitoring techniques, high public interest, and response to both immediate and long-term stressors.

Cooperrider et al. (1986) discuss the monitoring of songbirds, raptors, marsh birds and shorebirds, waterfowl, colonial waterbirds, and upland game birds. They recommended that efforts to attribute changes in bird populations to changes in habitat quality be tempered by the fact that most birds are highly vagile. Because they spend less than one third of the year on summer breeding grounds north of Mexico, migratory species could be more affected by habitat destruction and pesticide use in their wintering grounds in the Neotropics than by hazards in the United States. Songbirds in general are the easiest group of birds to monitor across a variety of habitats.

Although some raptors are difficult to detect and count because they occur at low densities in a variety of habitats (Kochert 1986), migratory raptors can be efficiently monitored (Bednarz et al. 1990). In western flyways raptors are monitored at five sites, and in eastern North America, at 35 sites (Hawk Migration Studies 1989). Marsh birds and shorebirds can easily be surveyed because they are often readily observable in open areas, but may require monitoring techniques quite different from those used for songbirds. Most species of waterfowl (ducks, geese, and swans) are migratory to some extent, and thus habitat features for different species will vary considerably throughout the year. Of the two major requirements for successful waterfowl production, availability of high-quality water areas and secure upland nesting habitat, the former is currently at a premium in the northern Great Plains and the latter in the prairie pothole area (Connors 1986). Upland game birds include partridge, grouse, turkey, quail, pigeons, and doves. These birds (at least the males) engage in vocalization that has a measurable seasonal and daily peak; monitoring during these peaks can reduce variability in the distribution of indicator values. In most instances a version of the auditory census for upland game birds will probably be the most efficient monitoring approach for EMAP (Eng 1986).

Any bird that predominantly feeds in aquatic systems and tends to nest in groups of closely associated nests is considered a colonial waterbird. Species of colonial waterbirds range from small storm petrels to large pelicans. And some, such as the petrel, lead a truly pelagic existence except when they come to offshore rocks and islands to nest. Most colonial waterbirds are near or at the highest trophic level of an ecosystem and are thus sensitive to changes in the health of other freshwater and marine organisms. Changes or reductions in biomass or species composition at lower trophic levels often cause stress in these birds, expressed as failure to breed, abandonment of eggs and young, late nesting, depressed growth rates, or reduced fledgling success (Speich 1986). Point counts should be useful for monitoring colonial water birds; estimates of some species can also be made from aerial photography.

9.2.1.2 *Amphibians and Reptiles*

Although amphibians and reptiles have received relatively little attention with regard to impact assessment, they are valuable indicators of ecological condition (Gibbons 1989; Hall 1980; Beiswenger 1989). Abundance and diversity fluctuate directly with changes in the composition and amount of microhabitats, and microhabitat changes often result from land management practices (Jones 1981; Ortega et al. 1982; Tinkle 1982; and Luckenbach and Bury 1983). Amphibians and reptiles are also important ecosystem components, and they make up large proportions of vertebrates in certain ecosystems (Bury and Raphael 1983). Measurements can be made on individual animals (Hall and Swineford 1981), entire communities (Scott 1982), or species' guilds. An indicator known as fluctuating (morphological) asymmetry provides a means of determining environmental exposure to certain contaminants (see Appendix G-1) and has been used for certain lizards (Leary and Allendorf 1989). True frogs (*Ranidae*) and toads (*Bufonidae*) are reported to be excellent indicators of both atmospheric and aquatic conditions. Long-term data (at least 10 years) are needed for reptiles and amphibians to separate subnominal condition due to anthropogenic stressors from that due to natural stressors such as climate variability.

The FWS National Ecological Research Center is currently investigating the disappearance of amphibians throughout the western United States (Corn et al. 1989; Corn and Fogleman 1984; Corn and Bury 1987; Freda and Dunson 1985; Pierce et al. 1984); this change appears to be occurring on a global scale. Because native fish and benthic organisms are still present at many of the western sites from which frogs and salamanders have disappeared, the amphibians appear to be more sensitive to some contaminants than other aquatic organisms. Amphibians respire cutaneously and thus may be exposed directly to atmospheric contaminants such as pesticides. Airborne contaminants become supersaturated in fog, and amphibians often respire out of the water during foggy conditions. The decline of these animals may be an early warning of change in ecological resource condition. Comparison of past versus present amphibian distributions (either abundance or presence/absence data), combined with tissue samples and atmospheric stressor data, can provide a useful tool in determining one aspect of ecological change.

Many lizards and certain toads are also excellent indicators of functional aspects of ecosystems (Pianka 1980; Short 1983). For example, Jones and Glinski (1985) and Jones (1989a) found that certain reptiles that dwell in leaf litter were lost from riparian ecosystems that were altered by stream impoundment. Species such as skinks (*Eumeces*) that are sensitive to changes in the processing of litter and organic material can be used as indicators of changes in ecosystem function. Measurements of species composition or simple presence/absence of guilds (e.g., species that increase with increased shrub cover) also have been used to detect changes in ecosystem function (e.g., Pianka 1980; Jones 1986; Jones 1989b).

Both amphibians and reptiles rank relatively high when judged against the EMAP indicator selection criteria (Table 9-2). Frogs, toads, and salamanders are top candidates for inland waters and wetlands, and salamanders are also favorable candidates for forests (Table 9-3). Lizards are top candidates in desert and grassland ecosystems, while turtles are favored in inland waters. When pitfall traps are arranged systematically and data are standardized by unit effort (e.g., season, arrangement, size) the results can be quantified and compared - for example, relative abundance of certain species between two or more habitat types (Jones 1986; Bury and Corn 1987). Pitfall traps are usually arranged along transects and will have a bias toward not sampling sedentary, microhabitat-specific animals or animals too large for the traps. Auditory, time-constant transects can be used to sample frogs and toads. This method requires training for sounds but is relatively inexpensive and nondestructive. Useful ancillary data for reptiles and amphibians include soils, litter, water availability, and horizontal extent of vegetation.

9.2.1.3 *Mammals*

Small mammals satisfy many of the criteria for indicator selection in Table 9-2. They respond to long-term stressors, have standard sampling methodology and existing data bases, and have a short generation time. Small mammals can be excellent indicators for arid lands and agroecosystems and good indicators for forests and wetlands (Table 9-3). Kapustka et al. (1989) discuss the problems with using small mammals as indicators, but they nevertheless recommend their use in assessments. Small mammals are easily collected, and their population parameters can be quantified reasonably well. For these reasons, it would be useful for EMAP to monitor changes in species composition and, where feasible, relative abundance of small mammals over time and in relation to landscape features.

9.2.1.4 *Invertebrates*

Many invertebrates rank high with regard to satisfying the selection criteria for indicators. Factors that support their application include their rapid responses to disturbances and their role as food sources for many other animals. Snails and slugs would be useful animal types for aquatic ecosystems or habitats near water; and grasshoppers, beetles, butterflies, bees, ants, and termites are most useful for monitoring terrestrial resource categories (Table 9-3).

The honey bee colony presents an opportunity to conduct testing at several levels of biological organization, from biochemical to population level. In addition, extrapolations to the community and ecosystem levels can be made by observing the pollination syndrome. Bees can be used for multimedia sampling, and body burdens of contaminants have been shown to correlate well with levels in environmental media. Bees can be used to monitor fairly large areas, as their flight range is 1.6 to 3 km (Kapustka et al. 1989). Bee colonies are inexpensive and practically self-sustaining test systems. Technical support is readily available from state and federal agencies, bee research laboratories, and bee keepers (Bromenshenk and Preston 1986). Sampling time varies from 5 to 20 min per hive, and samples should be taken from at least two to three hives at any terrestrial RSU (Kapustka et al. 1989).

Grasshoppers are numerous, occur in many habitats, respond sensitively to their environments, and are sufficiently diverse that particular sites may support a dozen or more species. Thus grasshoppers provide an animal assemblage whose shifting composition can be used to monitor change (Joern 1987).

Taxonomically and ecologically well known, butterflies are easy to sample and represent the ecologically important insect herbivore guild. They can be monitored by netting all species encountered at one or more transects within an RSU during an empirically determined, fixed-time period (e.g., 20 min per transect). Because of differences in species' phenologies, each site must be sampled at least twice a year (late spring/early summer and mid- to late summer).

9.2.1.5 *Summary*

The monitoring of ecological resources at regional scales requires serial collections of field measurements of animal species or guilds. EMAP should use existing animal monitoring programs when appropriate (e.g., Breeding Bird Survey), augmenting these activities when necessary. The U.S. Fish and Wildlife Service should be encouraged to help with the monitoring of certain animals. The high-priority research indicator for animals is relative abundance, when feasible, or presence/absence of select species. Animal types that would be useful to monitor in EMAP are presented in Table 9-3. For certain situations, it may be desirable to include particular sensitive or endangered species, or species that pose a direct threat to them (e.g., exotic or feral species). Morphological asymmetry and species demographics are considered additional research indicators for EMAP that are probably useful when applied to a specific hypothesis or when a problem is suspected. Animal indicators determined not to be appropriate for EMAP are discussed in Section 9.2.2. Habitat and landscape indicators are relevant to monitoring animals and are discussed in Section 9.4 and Appendix G-3. Climate data will be especially important for interpreting the data for animal response indicators.

9.2.2 Animal Indicators Not Appropriate for EMAP

Many types of animals will not be useful indicators of ecological condition for EMAP. In general, snakes are poor indicators of ecological condition because they are difficult to sample (Jones 1986). Large terrestrial mammals are heavily managed, and they are difficult to monitor. Three categories of indicators have proven to be poor indicators of ecological condition or to have limited value for examining possible causes of poor condition. These generally unsatisfactory indicators are (1) species richness, irrespective of species composition; (2) information-theoretic diversity indices; and (3) ecological indicator species as traditionally applied in land management decisions. While the concept of focusing on keystone species (species that play pivotal roles in ecosystems and upon which the diversity of a large part of the community depends) is initially appealing, in most situations we do not know what these species are.

Most ecologists will agree that biodiversity is *not* simply the number of species in a defined area. Richness is an important aspect of biodiversity, but knowing that one community contains 500 species, and another community 50 species, does not tell us much about the potential biodiversity within the community or the relative importance for conservation purposes. In fact, species richness can be a misleading indicator of biotic value, if many species in the sample are "weedy" or highly tolerant of human disturbance or pollution (Noss 1983). Thus, it is necessary to consider species composition (identity) in addition to species richness. Karr's Index of Biotic Integrity (IBI) does this to a great extent for aquatic systems (Karr et al. 1986).

Ecologists usually define "diversity" in a way that takes into consideration the relative frequency or abundance of each species or other entity, in addition to the number of entities in the collection. Several indices, primarily derived from information theory, combine richness with a measure of evenness of relative abundances (e.g., Shannon and Weaver 1949). Unfortunately, the number of indices and interpretations proliferated to the point where species diversity was in danger of becoming a "nonconcept" (Hurlbert 1971). Diversity indices result in considerable loss of information (such as species identity), heavily depend on sample size, and generally have fallen out of favor in the scientific community. As Pielou (1975) noted, "a community's diversity index is merely a single descriptive statistic, only one of the many needed to summarize its characteristics, and by itself, not very informative." Nevertheless, diversity indices still are used in misleading ways in some environmental assessments (Noss and Harris 1986).

Landres et al. (1988), in a critique of the uses of vertebrates as ecological indicators, defined an indicator species as "an organism whose characteristics (e.g., presence or absence, population density, dispersion, reproductive success) are used as an index of attributes too difficult, inconvenient, or expensive to measure for other species or environmental conditions of interest." The use of indicator species to monitor or assess environmental conditions is a firmly established tradition in ecology, environmental toxicology, pollution control, agriculture, forestry, and wildlife and range management. This tradition, however, has encountered many conceptual and procedural problems. In toxicity testing, for example, the usual assumption that responses at higher levels of biological organization can be predicted by single-species toxicity tests is not scientifically supportable (Cairns 1983). Hierarchy theory suggests that indication of effects across levels of ecological organization will be problematic. Of course, indicators at different levels of organization can be used to identify unhealthy resources, which then might require further monitoring to determine the extent of the problem. The magnitude of an ecological hazard becomes more evident as the number of animal indicators at different levels of organization indicate an unhealthy condition.

Landres et al. (1988) pointed out several difficulties with using indicator species to assess population trends of other species and to evaluate overall animal habitat quality. They also noted that the ecological criteria used to select indicators are often ambiguous and fallible. Norse et al. (1986) and Wilcove (1988) described how the "management indicator species" concept of the U.S.D.A. Forest Service, adopted as a result of the National Forest Management Act of 1976, is subject to bias when applied to forest planning. Conceding that traditions and regulations strongly support the continued use of indicator species, Landres et al. (1988) provide recommendations to make the use of indicators more scientifically rigorous and effective.

9.2.3 Research Needs for Animals

Animals could be considered the ultimate response indicators for EMAP in that animals are at the highest tropic levels within ecosystems, and thus are most responsive to changes in any ecosystem component.

However, animals are traditionally monitored in an intensive manner at a few sites. Once animal indicators are selected for various resource classes, field monitoring designs can be developed and tested to determine the required sampling densities and frequencies.

Knowing how sensitive animal community composition is to various levels of environmental stress is also required. Through the indicator evaluation process, data will be collected on the response of the animal community composition to known gradients of environmental factors. Although this is a "space replacing time" analysis and has the weaknesses of such research, EMAP needs such data in order to help explain observed trends in animal indicators. Also, whether the concept of keystone species is useful for EMAP needs to be determined, as well as whether demographic data are practical for the program.

EMAP should emphasize developing nondestructive and cost-effective sampling techniques for animals. The impact of and attitudes toward destructive sampling of animals for a national program must be considered carefully. Within a two-year time period, definitive studies could be accomplished that compare the information acquired by using visual sampling methods to that using sampling with transects of pitfall traps. Of course, visual sampling might be much more useful for some EMAP resource categories than others, such as arid lands versus forests. The use of automated sampling aids, such as tape recorders for birds and bats, should be investigated (Fenton et al. 1987; Thomas and West 1984). The application of biomarkers and animal indicators as diagnostic indicators in EMAP must be investigated further. For example, the analysis of mammal hair for contaminants might be an acceptable and powerful tool for determining contaminant exposure. Similarly, morphological asymmetry in individuals should be explored as a useful indicator of contaminant exposure.

A good index of terrestrial animal integrity would be useful to EMAP. Karr's IBI is used to evaluate compositional and functional changes in aquatic communities that may signal biotic deterioration (Karr et al. 1986). Water quality, habitat structure, energy source, flow regime, and biotic interactions are incorporated in the IBI. The IBI combines several sets of metrics on species richness and abundance in different trophic and functional categories, with measures of the health of individuals. Use of the IBI requires a reference site for comparison to determine degree of disturbance or perturbation. No terrestrial IBIs have yet been perfected; however, these problems probably are resolvable through further work.

9.3 BIOMARKERS

Biomarkers have recently received considerable attention among environmental toxicologists as a new and potentially very powerful and informative tool for detecting and documenting exposure to, and effects of, environmental contamination (McCarthy and Shugart 1990). Biomarkers are measurements that indicate, in biochemical or cellular terms, exposure of an organism to a chemical. Because of the commonality of biochemical and cellular structure and function among organisms, biomarkers are applicable to most ecological resource categories. Many animal biomarkers are applicable to both terrestrial and aquatic resources. Biomarkers have been developed for small mammals such as mice that are routinely used in laboratory research. The technique has also been applied to aquatic organisms, most often fish.

Most of the research on field evaluation of biomarkers has focused on marine and freshwater animals. In the terrestrial environment, biomarker measurements primarily have focused on birds. Extensive biomedical laboratory research with rodents and rabbits, however, suggests that biomarker approaches would be equally successful for other terrestrial animals. Nevertheless, field evaluation of biomarkers in terrestrial animals is limited. The lack of experience and data on biomarker responses suggests that the initial application of biomarker techniques in a regional monitoring survey such as EMAP should be focused on aquatic animals and that the monitoring of biomarkers for terrestrial animals should be limited to a few trial locations.

More information on biomarkers is available for terrestrial plants than for aquatic macrophytes or algae. For terrestrial plants, however, most research has centered on the effects of gaseous pollutants (NO_x, SO_2, O_3). Only a few plant biomarkers have been identified that respond to toxic environmental pollutants.

Biomarkers are often divided into those that indicate exposure to hazards and those that demonstrate toxic effects resulting from the exposure. Biomarkers of exposure are defined as (1) an exogenous substance within a system, (2) the interactive product between a xenobiotic compound and endogenous components, or (3) some other event in the biological system related to exposure. Exposure biomarkers may include measures of internal dose or the biologically effective dose, that is, the amount of material interacting with critical subcellular, cellular, and tissue targets or with an established surrogate (National Research Council 1987).

An effects biomarker is defined as (1) an indicator of an endogenous component of the biological system, (2) a measure of the functional capacity of the system, or (3) an altered state of the system that is recognized as impairment or disease. These conditions include an actual health impairment or a recognizable disease, an early precursor of a disease process that indicates a potential for impairment of health, or an event peripheral to any disease process, but correlated with it and thus predictive of development of impaired health (National Research Council 1987).

9.3.1 Identification of Biomarkers For EMAP

The primary application of biomarkers within EMAP would be as exposure indicators; however, some biomarkers can be used as response indicators. A conceptual view of how biomarkers may be useful is shown in Figure 9-1. Biomarkers provide information that complements and extends other exposure indicators, such as analyses of ambient chemicals, toxicity tests, and measurement of body burdens of toxic chemicals. In general, biomarkers measured in organisms collected from (or confined to) monitoring sites would be used to determine whether the subnominal status of an ecological resource is correlated with toxic chemicals in the environment. Some categories of biomarkers (e.g., immunological and physiological/bioenergetic biomarkers) also are sensitive indicators of organismal response to nonchemical stress, such as pathogens.

Biomarkers identified as appropriate for EMAP are listed in Table 9-2 and discussed in detail in Appendix G-2. A few additional biomarkers specific to an ecological resource category (e.g., forests) are included in the indicator strategies (Sections 3-8). Although there are many more biomarkers than those discussed in this section, these are proposed as appropriate research biomarkers after considering the EMAP indicator selection criteria (Table 2-1). The selection and descriptions of biomarkers reflect the cumulative knowledge and insights of approximately 50 experts who participated in a biomarker workshop in Keystone, Colorado, in July 1989 sponsored by the Society of Environmental Toxicology and Chemistry. The complete report of this workshop contains a comprehensive review of the state of science on biomarkers (Hugget 1990). There are several reasons for not considering any biomarker as a high-priority research indicator for EMAP. Although biomarkers show great promise as response indicators, more research is needed to understand the significance of a change or trend in measurements and to allow the interpretation of exactly what factor or agent induced the biomarker response. The feasibility of monitoring terrestrial animals within EMAP for both population (Section 9.2) and biomarker indicators also needs further evaluation. In addition, most biomarker monitoring requires destructive sampling for small animals, birds, and fish; and the impacts and applicability of such sampling at regional and national scales need to be seriously evaluated.

Animals in the natural environment are exposed to a variety of stresses, including sublethal levels of contaminants, unfavorable or fluctuating temperatures, elevated sediment loads, hypoxia, and limited food availability. These factors, singly or in combination, can impose considerable stress on physiological systems (Weidemeyer et al. 1984). Stress that exceeds the tolerance limits of organisms is obvious because it is normally lethal. Sublethal stress is more insidious because adverse effects are generally manifested subtly at

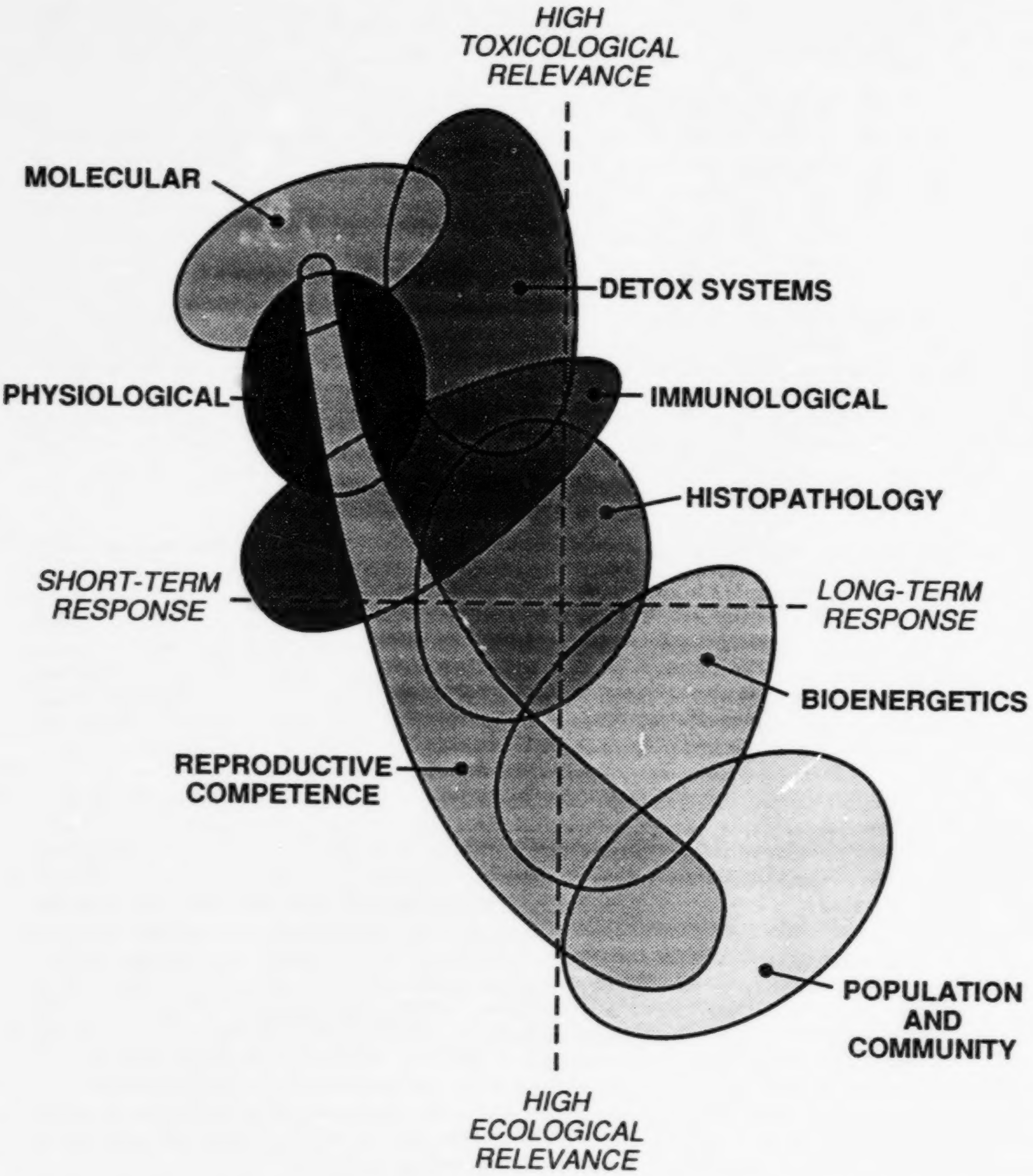

Figure 9-1. Conceptual view of how biomarkers may be useful to EMAP (Source: Adams et al. 1990).

the biochemical or cellular level. However, depending on its severity, sublethal stress, can reduce growth, impair reproduction, predispose organisms to infectious diseases, and reduce the capacity of the organism to tolerate other types of stress, including exposure to toxic chemicals. At the population level, effects of stress may be manifested as reduced recruitment and depletion of compensatory reserves. Many effects biomarkers (histological, immunological, and physiological/bioenergetic biomarkers) are sensitive and informative measures of the organism's response to cumulative stress introduced through chemical, physical, or pathogenic sources.

Measurements of chemical concentrations in environmental media are specific, quantitative, sensitive, and precise. The biological significance of the chemical concentrations measured in air, water, soil, or food is, however, not at all clear. We currently understand the toxic action of only a few of the thousands of chemicals in the environment. Almost no information is available on the interactions of complex mixtures of chemicals, or on the role of environmental stresses on an organism's susceptibility to toxic exposure. Furthermore, a chemical survey is a snapshot in time and space. Surveys will not capture variations in concentrations over time that result from intermittent exposures such as storm events or releases of effluents by industries. Spatial patchiness of contaminant patterns also requires extensive and expensive sampling and chemical analyses. Biomarkers offer an alternative way to monitor and interpret environmental conditions.

Evidence of exposure provides a temporally integrated measure of bioavailable contaminant levels and is therefore much more relevant to the risk posed to the organism by the environment than is the concentration of contaminants in soil, water, or air. Furthermore, mobile organisms integrate exposure over their spatial range, and measurements on such organisms can help overcome problems of patchiness of ambient chemicals. For analyses of exposure to complex mixtures of chemicals, biomarkers provide an opportunity to examine the pharmacokinetic and toxicological interactions within exposed organisms as well the cumulative impact of toxic exposure. These attributes make biomarkers especially appropriate for application in a regional monitoring survey such as EMAP.

Toxicity tests (laboratory bioassays) have proven very useful in detecting and quantifying adverse effects of individual chemicals, mixtures, effluents, and sediments. Toxicity tests have limitations, however, because they do not necessarily account for the effect of (1) chemical speciation in the environment, (2) kinetics and hysteresis in sorption of chemicals to sediment, (3) accumulation through food chains, and (4) modes of toxic action which are not readily measured as short-term (7- to 21-day) effects on survival, growth, or reproduction. In situ monitoring of organisms collected or confined near discharges is a more realistic approach for determining the integrated exposure and effect of environmental pollutants. The combination of laboratory toxicity test data with demonstration of *in situ* effects in receiving bodies provides a compelling logical link between toxicity test results and effects observed in the environment.

Biomarkers may also prove to be a useful addition to conventional survival and toxicity tests for detecting other mechanisms of toxic action. For example, a growth assay using larvae could be useful for detecting genotoxic effects if the larvae also were examined for DNA alterations at the end of the regular test period.

Measurement of tissue concentrations is highly recommended as an indicator of exposure to persistent compounds such as metals and certain classes of organic chemicals such as many polychlorinated compounds. In EMAP, tissue concentrations are considered to be an exposure indicator that is distinct from biomarkers. However, when measuring tissue residues is not feasible, such as with compounds that do not readily bioaccumulate (because of rapid metabolism, for example) or with complex mixtures that require time-intensive and costly analyses that may not identify all toxic chemicals, indirect measures of exposure (biomarkers) may be required or preferred. In addition, since the relationship between tissue concentrations and toxic effects is complex and not fully understood, biomarker measurements may indicate a response that is of toxicological significance.

9.3.2 The Application of Biomarkers in EMAP

The results of population monitoring are the ultimate indicators of ecological effects. However, population responses such as occurrence, abundance, and reproduction do not provide an indication of their cause. Correlation of population parameters with body burdens of chemicals and with sensitive and responsive molecular and biochemical biomarkers of exposure is supporting evidence for a causal linkage between exposure and effects. Correlations of population parameters with ambient concentrations of chemicals or indices of chemical loading provide additional support for a causal link between chemical releases into the environment and ecological effects. Nevertheless, although data from population monitoring can provide valuable information on ecological condition, such data tend to be rather insensitive indicators of effects because of the variability of animal populations and the imprecision of estimates from field monitoring. Therefore, it may be useful to monitor biomarkers to provide a more sensitive and precise indicator of the nature and magnitude of effects, and to gain insights into what may have caused the effects. The correlations between the effects biomarkers and exposure indicators are expected to be better than those between the population monitoring parameters and the exposure indicators.

Conceptually, the use of both exposure and habitat indicators and response indicators within EMAP will permit preliminary identification of possible reasons for ecologically relevant effects. Responses at the population and community level are highly relevant to ecological conditions, but such responses are slow and are difficult to attribute unequivocally to toxicants. In contrast, responses at lower levels of organization are more rapid and can be more clearly linked to toxic exposure; however, it is difficult to relate these responses to effects at the community level. Our approach is to measure responses at several different levels of biological organization, including metrics of both exposure to toxicants (generally responses in the upper left quadrant of Figure 9-1, but also including tissue burdens of chemicals) and effects (generally the lower right quadrant).

The division between biomarkers of exposure and biomarkers of effects is arbitrary. This lack of a discrete separation is a natural consequence of the interdependence inherent in the organization of biological systems. The goal in examining responses at these different levels of organization is to answer two critical questions.

1. Are organisms exposed to levels of toxicants that exceed the capacity of normal detoxication and repair systems?

2. If there is evidence of exposure, i.e., is the chemical stress consistent with observed impacts on the condition of the populations or communities?

Evidence of exposure from analyses of ambient chemicals, toxicity tests, or tissue concentrations and from biomarker responses at lower levels of biological organization can provide an answer to the first question. In particular, biomarkers of exposure indicate the biological significance of chemicals that may have entered the organism; that is, did the chemical reach molecular and biochemical targets and cause detectable damage or induce a protective response? The second question can be addressed by determining whether the responses to the toxicants are propagated through successively higher levels of biological organization (biomarkers of effects and population parameters). If chemical exposure is responsible for a high-level ecological effect, responses should be apparent at intermediate levels of organization. Alternatively, if evidence of chemical exposure is not revealed, or if biomarker responses indicate effects only in the most sensitive and responsive exposure parameters (e.g., genetic damage), and not at higher levels of biological organization (e.g., histopathological evidence of neoplasia or tumors, or reduced growth or other measures of fish health), community- and population-level effects could not be reasonably attributed to chemical agents.

Some biomarkers are general indicators of exposure or effects, and others are indicative of particular chemicals or classes of chemicals. For example, inhibition of the enzyme aminolevulinic dehydrase is a specific indicator of exposure to lead, induction of the cytochrome P450 monooxygenase system is a specific response to organic contaminants such as polycyclic aromatic hydrocarbons, and detection of DNA or protein adducts demonstrate exposure to specific chemicals. Conversely, other biomarkers provide evidence of responses to chemicals but are not specific to one or a group of toxic agents. For example, DNA integrity can be adversely affected by chemical modification of DNA, physical damage from ionizing radiation or ultraviolet light, or inhibition of DNA repair systems. Similarly, induction of heat-shock stress proteins is a general indicator of response to a wide range of chemical or physical insults. Both types of biomarkers are useful, but may be most appropriately used at different tiers of a monitoring program. General indicators can be sensitive tools for screening studies to determine in a cost-effective manner if there is any evidence of stress. If these general biomarkers suggest a problem, a second tier of testing with more specific biomarkers may be warranted.

9.3.3 Sampling Considerations For Animal Biomarkers

The pathways of exposure and spatial range of animals are among the criteria that should be considered when selecting species for monitoring. The habitat and food preferences of monitored species are important factors that may aid in identifying the sources and routes of exposure. Fish and other aquatic species are exposed through surface waters and sediment, and comparison of water-column-associated species and sediment-associated species can distinguish the contribution of sediment to exposure. Similarly, herbivorous rodents, such as voles and some mice, provide information on different pathways of exposure than those for muskrats and some shrews that dig in the soil (e.g., Loar et al. 1989).

In general, for chemicals such as metals that are not biomagnified, physical position of organisms in the environment may be more important than trophic position in determining exposure. Typically, soil- or sediment-associated organisms display the highest tissue concentrations of contaminating metals and may be most useful for measuring biomarkers of exposure to metals (e.g., Martin and Coughtrey 1982). For compounds such as persistent lipophilic chemicals (polychlorinated biphenyls and polycyclic aromatic hydrocarbons), accumulation through trophic levels may be the most important exposure pathway (e.g., Thomann 1981).

Confined animals can be used to test hypotheses about different pathways of exposure. Confinement can limit access to defined exposure pathways. For example, animals can be provided with clean water and denied access to surface water, or vegetation can be removed from an enclosure and the animals can be provided with uncontaminated food. Agricultural livestock that drink well water can serve as sentinels of ground water quality.

The home range area of an animal must match the size of the study site and the degree of geographic resolution required for a particular study. For example, voles, which range within an area of approximately 400 m^2, were useful for studying local sites such as Love Canal (Christian 1983). Larger sites might permit the use of rabbits or groundhogs, which range over hectares and therefore integrate exposure over a wider geographic area. Bluegill sunfish have been useful in studies of contaminated streams because tag-recapture studies have demonstrated they are confined to a 100-m reach in the streams (Loar et al. 1989). Sessile animals, such as clam or mussel colonies, provide accurate spatial resolution; however, other animals that are somewhat mobile can avoid very isolated "hot spots" of contamination. Animals can be confined in order to increase the degree of geographic resolution in observations, to confirm and test hypotheses about the location of contaminants, and to test for the presence of localized "hot spots" of pollutants.

Index periods for sampling are important because responses of many candidate biomarkers can vary, depending on physiological and environmental factors such as sex, reproductive condition, temperature, and food availability. As discussed for individual biomarkers in Appendix G-2, certain times of the year are likely to be inappropriate for biomarker surveys. More importantly, if responses of organisms from different geographic locations are to be compared, organisms should be collected so that seasonal and internal physiological influences are similar among sites. For example, responses of poikilothermic organisms collected in winter cannot be compared with those from the same species collected during other seasons; likewise, for some indicators, responses of reproductively active females should not be compared to those from males or immature females.

9.3.4 Research Needs for Biomarkers

The development, application, validation, and interpretation of biomarkers is a relatively new field of research. With few exceptions, even those biomarkers considered to be well understood and validated lack a historical data base comparable to more traditional methods for indicating exposure, such as analysis of ambient chemical concentrations or standard toxicity tests.

Many biomarkers are still research tools. Methods have not been standardized, and many biomarker assays require fairly sophisticated equipment. Standardizing techniques and developing quality assurance/quality control procedures are presently being considered by the American Society for Testing and Materials (ASTM), but it is likely to be several years before definitive standards are developed and accepted by ASTM. Many biomarker methods could be easily simplified and measurement costs could be decreased by economy of scale if large numbers of samples were processed and automated clinical equipment were available. For example, research-grade spectrophotometers and fluorometers are not required for enzyme biomarkers; these assays can be easily adapted to highly automated centrifugal analyzers that are routinely used for human and veterinary blood chemistry profiles. Likewise, development of monoclonal antibodies could replace sophisticated and time-consuming quantification of metabolites or proteins with simple, quick (even field-portable) enzyme-linked immunosorbent assay kits. Until very recently, there has been little or no incentive to implement these improvements, but the increased interest in applying biomarkers suggests that this situation will change in the near future.

The biomarkers recommended for EMAP are qualitative indicators of exposure, and the significance of biomarker responses must be interpreted within the context of how they correlate with the better documented exposure indicators. Nevertheless, biomarkers can provide valuable and informative data that will corroborate and extend other diagnostic indicators, and the significant long-term advantages that biomarkers offer for EMAP counterbalance the limitations imposed by their currently limited data base in the short term.

9.4 LANDSCAPE AND HABITAT INDICATORS

Indicators of habitat structure and landscape pattern will be very important for characterization of potential habitat for animals; animal monitoring will be limited because of the large geographic focus and limited sampling frequencies of EMAP. EMAP needs indicators of habitat structure and landscape pattern that can be measured efficiently through remote sensing, entered in digital format into a Geographic Information System, and related directly to aspects of terrestrial and aquatic ecosystems. Several of the indices described in Section 9.4 represent progress in this direction. However, no good indicators of connectivity, juxtaposition, and many other aspects of landscape ecology exist that are relevant to animal biodiversity. In addition, the relationship between changes in landscape indicators and their effect on animal species or guilds needs to be quantified. Such relationships will most likely be developed first for birds at the regional scale because of the extensive data available in the BBS.

EMAP needs some indicators for monitoring ecological structure across large geographic areas, both within and across EMAP resource categories. Landscape and habitat indicators are appropriate for this and can be developed from data bases compiled as a result of the EMAP landscape characterization activities. Landscape indicators describe the spatial pattern of the landscape in a horizontal plane, while habitat indicators usually emphasize the vertical plane and focus on a relatively smaller scale. Both can be used to quantify the general structure of ecological resources. Some landscape indicators are well established (e.g., proportions of land use or land cover, drainage density, patch size), and others have been proposed only recently (e.g., fractal dimension, contagion). Similarly, research on the Habitat Layers Index (HLI) has been ongoing for several years at local areas, but its application to large geographic areas has only recently been proposed.

9.4.1 Identification of Landscape and Habitat Indicators

9.4.1.1 *Landscape Indicators*

Landscape indicators that could be useful for EMAP are listed in Table 9-2. Landscape indicators (or indices as in O'Neill et al. [1988a]) are calculated by using algorithms applied to land-use/land cover data for the purpose of quantifying significant landscape pattern in a single number. It is likely that several landscape indicators may be necessary for adequate characterization of pattern, depending on the complexity of the landscape and the assessment endpoint. Two criteria were used to evaluate landscape indicators. First, the landscape parameter must be easy to measure, for example, by using remotely sensed imagery. Second, the measure must be readily interpretable in ecological terms; that is, it must be possible to interpret a change in the indicator in terms that have immediate meaning for the environment. While landscape indicators obviously describe the horizontal landscape pattern, they can also be linked to ecological processes such as nutrient cycling (Osborne and Wiley 1988; Peterjohn and Correll 1984) to wildlife migrations (Freemark and Merriam 1986; Noss 1983; O'Neill et al. 1988b; van Dorp and Opdam 1987), and to susceptibility of an ecological resource to a disturbance such as fire or insect attack (Turner (1987; Sharpe et al. 1987; Hayes et al. 1987).

Six landscape indicators were identified as appropriate for EMAP and are discussed in detail in Appendix G-3; four of these, habitat proportions, patch size and perimeter-to-area ratio, fractal dimension, and contagion were designated high-priority research indicators because they have been applied to large geographic areas.

9.4.1.2 *Habitat Indicators*

Two high-priority habitat indicators are proposed for EMAP: the abundance or density of key physical features and structural elements and the linear classification and physical structure of habitat (LCPSH). Research in many different resource categories has demonstrated that certain physical features of habitats (e.g., cliffs, outcrops, sinks, seeps, tallus, slopes) and structural elements (e.g., snags, downed logs) are critical to animal diversity and abundance. The abundance or density of such features or structural elements is therefore an important indicator of potential habitat for animals. This indicator contains more detailed information than the surface cover features included in the LCPSH.

The three-dimensional structure of terrestrial habitats can influence the diversity of animal communities. Short and Williamson (1986) developed methods to (1) measure habitat structure for inventory and assessment work, (2) describe the relative structural complexity of different landscapes, (3) describe the direction and rate of change in habitat structure over time, and (4) describe the potential distribution of animal species having particular dependencies on the specialized structure of habitats. The HLI describes the relative structural complexity of habitat for an area by comparing the number of habitat layers present and the total area of those habitat layers with the most complex habitat structure that could occur in that area. Habitat layers provide the framework of the species-habitat matrix used in the formulation of habitat guilds (Short 1983). This HLI emphasizes the vertical structure of habitats, because birds (e.g., Karr 1971; Rabenold 1978; Geibert 1979), mammals (Maser et al. 1981), and herpetofauna (Heatwole 1982) are dependent on the vertical dimension of vegetation communities. The HLI is predictive of species richness for birds and vertebrates. It is an objective, quantitive measure because habitat layers have finite definitions and can be counted and measured from aerial photography with ground verification or from field visits.

Other habitat indicators and relative abundance and location of plant food sources for selected animals can be monitored at the same time.

The LCPSH is a simplification of the HLI (three or four layers only) and is an extension of the HLI from the local to the regional scale. The LCPSH is proposed as a high-priority research indicator that can be used to monitor important habitat variables for terrestrial animals over long time periods and across large geographic areas. It uses a standard sampling format and standard sampling procedures and can be applied to all terrestrial resources and to certain wetland resource classes. The LCPSH thus can be used to monitor important animal habitat variables both within and across resource categories, can use both map-based and field survey data, and provides individual numeric values for a variety of different habitat features including habitat layers, surface cover features (e.g., sand, asphalt, rock), and vegetation variables within the understory, midstory, and overstory layers. The values for different metrics from an RSU provide a "signature" for that unit. The signature then can be compared among RSUs and over time and can be used to develop summaries that describe the condition of potential animal habitats for a region or the impacts of different land-use changes on important animal habitat metrics.

The LCPSH is proposed as an EMAP indicator that is especially relevant for comparison among regions. It can describe potential habitat and vegetation structure and, when applied over time, can describe rates and magnitude of changes in land use, plant succession, desertification, etc. Indicators for horizontal landscape pattern can also describe potential animal habitat, as well as general ecological condition, pollutant loadings, and susceptibility of a resource to disturbance such as fire or insect attack.

9.4.2 Landscape Indicators Not Appropriate for EMAP

Numerous other metrics have been proposed to describe the pattern or texture of landscapes. Many of these have been developed for analysis with remotely sensed imagery (Haralick and Anderson 1971; Haralick and Shanmugam 1974). As many as 16 texture indices have been proposed (Haralick et al. 1973), but analyses reveal that they are highly correlated and thus are simply different ways of presenting the same information. The few indices that are statistically independent do not appear to correspond in any obvious way to ecological processes on the landscape. While these texture indices may be useful for classification of satellite imagery, we conclude that alone they would not make useful landscape indicators.

9.4.3 Research Needs for Landscape and Habitat Indicators

While many studies have shown the importance of relationships between landscape pattern and ecological processes, we have only begun to investigate the usefulness of landscape pattern in understanding ecosystem function. Additional research is needed to quantify the influence of data resolution and spatial extent on the characterization of landscape pattern. Additional work is also needed on quantifying the relationships between landscape indices and ecological processes in order to incorporate spatial pattern into regional ecological risk assessments. A landscape ecology research program is being developed as part of the EMAP Landscape Characterization activity.

The position of ecotone boundaries on the landscape may eventually become the most sensitive and practical method for large-scale, long-term monitoring (di Castri et al. 1988). Predicted climate changes due to increasing CO_2 concentrations would result in temperature changes of a few degrees and changes in seasonal precipitation patterns, both of which occur in time frames of decades to centuries. Thus unidirectional trends will be difficult to detect in population, community, or ecosystem parameters. During the latest glacial periods, climate change showed its most dramatic ecological effects in the geographic repositioning of those ecotones between major vegetation types. This effect was far more dramatic than, for example, the loss of species or alterations in energy flow and nutrient cycling. It is likely that future long-term changes in climate, and similar slow but pervading changes in the environment, will also be reflected in the movement of ecotones. Ecotone movement should be measurable in field surveys where the geographic limit of a species range occurs and especially where this coincides with steep topography which amplifies the latitudinal gradient. Such changes could be detected on transects across current ecotones. Monitoring of these transects could probably be accomplished by the analysis of remotely sensed data. The ability to monitor large ecotones will be investigated by using the EMAP Characterization data base.

9.5 STRESSOR INDICATORS

Stressor indicators are physical, chemical, biological, social, and economic data or information on human activities that can cause environmental disturbance. All indicators that are not response, exposure, or habitat indicators are stressor indicators. Generally, stressors will not be measured by EMAP. Much of the data on stressor indicators will be provided by EMAP-Characterization, and additional data will be compiled from other local, state, and federal data bases. Examples of stressors include land use, contaminant use, air pollution, number of hazardous waste sites or wastewater discharges, and road density. While resource categories may have many stressors in common, some will be unique to a category. Examples of stressor indicators for inland surface waters include pollutant loadings as measured or estimated at point sources and as calculated from land uses, flow and channel modification, and species introductions. These represent chemical, physical, and biological stressors, respectively. Stressor indicators for agroecosystems include chemical usage in and export from agroecosystems and number and size of farms. Climate and weather represent stressors important to all resource categories, and resource management practices are stressors to many ecological resources. A discussion of atmospheric stressors that EMAP may monitor is the topic of Section 10.

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SECTION 10

INDICATOR STRATEGY FOR ATMOSPHERIC STRESSORS

Steven Bromberg[1]

10.1 INTRODUCTION

Sections 3 through 9 describe response, exposure, and habitat (on-frame) indicators that are proposed as research indicators for the respective EMAP resource categories. This section addresses atmospheric stressors (e.g., gases, particles, UV-B), the only indicators to date that will be field-monitored by EMAP outside the resource sampling units (off-frame).

As a result of requirements of the Clean Air Act and subsequent amendments, most of the atmospheric exposure monitoring projects being performed in this country are concentrated in urban areas. This focus has resulted in a notable lack of data that describe exposure regimes in nonurban locations. Only during the past several years have attempts been made to characterize atmospheric exposure in relatively unpopulated areas.

Several networks in nonurban areas have been deployed in support of the National Acid Precipitation Assessment Program (NAPAP), established in 1980. The National Acid Deposition Program/National Trends Network (NADP/NTN) is collecting weekly samples of wet precipitation measurements from approximately 200 sites distributed nationwide. The National Dry Deposition Network (NDDN) has been in operation since 1986 and is collecting air-related samples and data on meteorology from approximately 50 sites, located primarily in the East. The National Park Service (NPS) has deployed air concentration samplers for ozone, sulfur dioxide, sulfate, and nitrate throughout the federal park system. The long-term continuation of these networks upon completion of NAPAP remains questionable, however.

If a nonurban monitoring program is implemented by EMAP-Air and Deposition, presently operating sites that can contribute to the EMAP mission must be maintained. Loss of existing expertise, interruption of long-term data sequences, and closure of current sites as a result of discontinuing these networks would be inefficient because of the prohibitively high costs to initiate entirely new networks. Thus, EMAP must take advantage of all appropriate existing collecting systems to avoid duplication, to achieve an active data-gathering system as quickly as possible, and to gather data in the most economical manner.

The primary goal of EMAP - Air and Deposition is to be able to provide, on a seasonal and annual basis, regional estimates of exposure with known accuracy and precision. A secondary goal is to provide interpolated estimates of exposure at a particular location, also with known precision and accuracy. Exposure will initially be expressed in concentration units; as technology allows and ecosystem researchers become adept at using flux information, exposure will be expressed in deposition units.

The suite of candidate variables to be sampled was extensive; each EMAP resource group had to be very restrictive in selecting atmospheric contaminants as research indicators for their resource category. In some cases, contaminants of importance to all categories would be collected throughout the network; however, pollutants of special importance to a particular resource class and/or region would be monitored only at selected locations.

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10.2 ATMOSPHERIC INDICATORS APPROPRIATE FOR EMAP

Figure 10-1 lists the proposed research indicators of atmospheric stressors. A written external peer review of these indicators was performed in April 1990 (Appendix I.8), followed by a review by the EPA Science Advisory Board in May 1990. Enclosed in parentheses following each research indicator description below is the indicator identification code for easy reference to the corresponding fact sheets in Appendix H.

10.2.1 High-Priority Research Indicators

The classification of atmospheric indicators as having high-priority research status, while necessarily subjective, was based on our review of the literature and experience with atmospheric deposition monitoring programs.

Ozone: Ozone is a transformation product of atmospheric emissions that is regulated by EPA National Ambient Air Quality Standards and is considered a stress to ecological resources as well as to human health. The deposition of and exposure to ozone affect vegetation through disruption of physiological processes. (H.1)

Sulfur Dioxide: Sulfur dioxide is a product of atmospheric emissions that is regulated by EPA National Ambient Air Quality Standards and is considered a stress to ecological resources as well as human health. The deposition of and exposure to sulfur dioxide affect vegetation through disruption of physiological processes. (H.2)

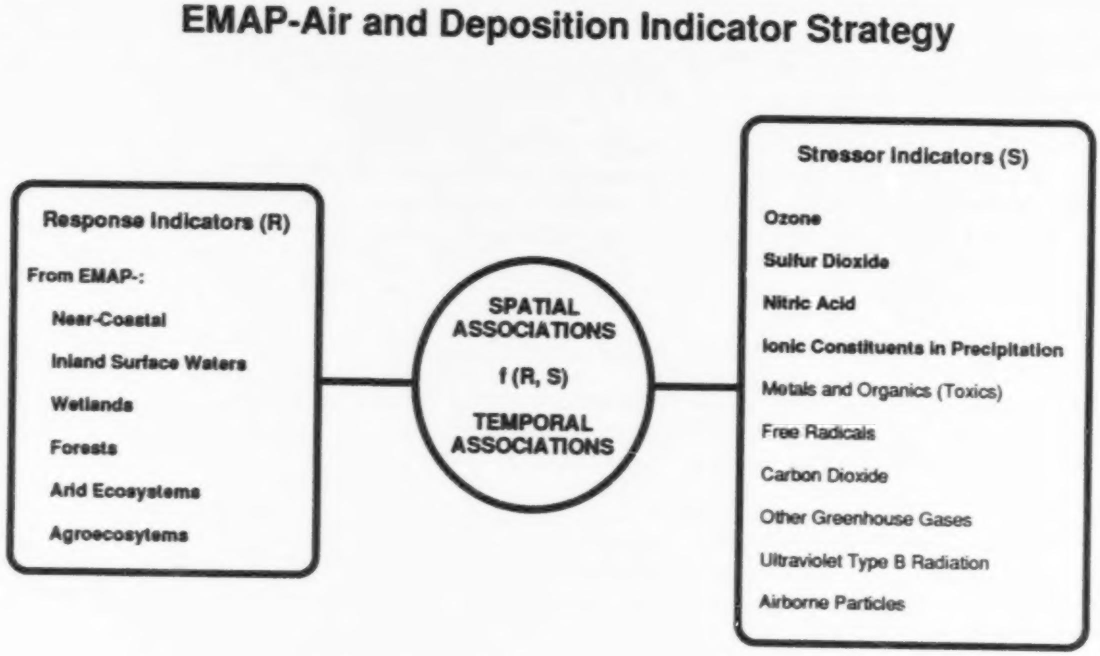

Figure 10-1. **Diagram of the proposed EMAP-Air and Deposition Indicator Strategy. Indicators in bold lettering are high-priority research indicators.**

Nitric Acid: Nitric acid is a transformation product of atmospheric emissions. Nitric acid is not presently regulated by EPA; however, it is considered a stress to ecological resources as well as human health. The deposition of and exposure to nitric acid are thought to affect vegetation through disruption of physiological processes. (H.3)

Ionic Constituents in Precipitation: Nine major ions in wetfall are identified that may have direct impacts on terrestrial vegetation and aquatic biota through such processes as acidification, or indirect impacts by disruptions in nutrient cycling. (H.4)

10.2.2 Other Research Indicators

Several research indicators that could have significant impacts on ecological resources are insufficiently developed for immediate evaluation and are being considered for development and refinement by EMAP-Air and Deposition. Research indicators currently under consideration include those described below.

Metals and Organics (Toxics): The effects from chronic deposition of airborne toxic chemicals on terrestrial and aquatic organisms and their potential interaction with other stressors to induce antagonistic or synergistic effects are unknown. The persistence of these compounds can result in adverse biological effects by incorporation and accumulation into food chains and disruption of ecological processes. (H.5)

Free Radicals: Products of oxidation reactions in the atmosphere, these short-lived compounds are highly energetic and, upon exposure to vegetation, could be disruptive of its normal biochemistry. (H.6)

Carbon Dioxide: Although not the greatest absorber of infrared radiation per molecule, the huge flux of carbon into the troposphere by fossil fuel sources has made carbon dioxide a leading factor in long-term global climate trends and its consequential effects on ecological resources. This indirect climate effect and the direct fertilization effect of increasing carbon dioxide concentrations on all vegetation types makes it a potentially important atmospheric stressor. (H.7)

Other Greenhouse Gases: The chemistry of the free troposphere is characterized by gases which absorb infrared radiation yet have little direct effect on vegetation, and their increase has led to the greenhouse theory of global warming. (H.8)

Ultraviolet Type B Radiation: Increased UV-B exposure to terrestrial organisms may have a significant effect on reproduction. Increased intensity may also stress aquatic microorganisms, which in turn would affect organisms of higher trophic levels. (H.9)

Airborne Particles: Extremes of particle loading in the atmosphere from sources such as severe dust storms, volcanic activity, and power plants could have short-term effects on ecological resources. Particle loading is also related to atmospheric extinction and the environmental value of visibility. (H.10)

10.3 ATMOSPHERIC MONITORING STRATEGY

Where possible, it is imperative to build on current monitoring systems. EMAP, however, will be very selective in choosing existing sites for incorporation into the monitoring system. Only if sites fulfill the EMAP design criteria will they be incorporated. If located at an existing ecosystem research site or near a Tier 2 resource sampling unit, existing wet and dry deposition sites would be incorporated into the EMAP atmospheric exposure monitoring network. Sites from NADP/NTN, NDDN, NPS, and selected states would be used as both wet and dry deposition monitoring locations. The network would be supplemented with new sites as needed, or with additional equipment as appropriate.

The first task would be to determine how well existing sites describe exposure on a regional basis or when interpolating between monitoring sites. An evaluation of the ability to detect directional trends is also necessary. Results of these analyses would indicate where additional sites are needed and which sites are duplicative. These analyses also would reveal where improvements in accuracy and precision are required in order to ensure directional trends can be detected.

Using a combination of existing sites, relocated sites, and new sites, an optimum network design would enable EMAP researchers to obtain seasonal and annual estimates of regional exposures to selected pollutants with known precision and accuracy. Estimates of precision and accuracy for interpolated values at selected points by techniques such as kriging would also be available.

Several options are available for deploying the atmospheric monitoring network. Intensive monitoring sites can be operated that provide data of relatively high temporal resolution (e.g., continuous ozone and meteorological data, weekly particulate data). These sites are sophisticated, require highly trained operators, and are costly to install and maintain. The resulting data, however, are of high accuracy and precision. The site density of such a network would probably be relatively low because of capital and operating costs.

A second option is to install passive monitoring sites. Samplers installed at these sites could collect contaminants by diffusing gases onto an adsorbent. Data collected by this method, however, are not very accurate or precise, and monitors are not available for many of the constituents of interest. The advantage is that such monitors are relatively inexpensive to install and operate, enabling many monitors to be deployed for the same cost as a few of the intensive sites. More monitors would provide better spatial coverage than would the intensive sites, but with much reduced accuracy.

The third option is to use a combination of active monitors at intensive sites and passive monitors at extensive sites. A small number of intensive sites would be retained to provide accurate data. The passive samplers would be deployed in a relatively dense network to yield required spatial resolution. Data from the passive monitors would be compared with that from the active monitors to ensure that a consistent relationship exists between the techniques. During the network evaluation and design phase of the project, these deployment options would be examined.

Regardless of the option selected, regional estimates of exposure with known accuracy and precision will be provided. The degree of accuracy and precision available would depend on the selected approach; the option selected would depend on resources available and on identified assessment needs. If interpolated estimates are inadequate for a particular location, additional equipment will be installed to satisfy the existing need.

10.4 RESEARCH NEEDS

Research needs fall into two categories. Development and improvement of sampling and analytical methods are needed for most atmospheric stressors, particularly for toxic pollutants. These improvements are required to enhance methods sensitivity, simplify sampling and analytical procedures, and reduce costs.

The second area of required research is the development of data analysis and display techniques. Combining data from various networks of differing precision and accuracy for use in network analysis is a particular need. New and improved techniques for displaying temporal changes and regional patterns are required for better presentation of research results.

SECTION 11

SUMMARY AND FUTURE DIRECTIONS

Section 1 emphasized several purposes of this document including: (1) information transfer, (2) program integration, and (3) solicitation of input from the scientific community. Sections 2 through 10 explained the rationale and framework for identifying and prioritizing indicators for further evaluation, for both the program in general and for each ecological resource category. The appendices provide details on each indicator discussed in Sections 3 through 10. This section represents the information transfer purpose of this document.

A critical element of EMAP is program integration, one aspect of which is to adopt a common philosophy and nomenclature for indicators among ecological resource categories. Section 2 establishes the framework for the EMAP indicatory strategy and provides general guidance to scientists who are identifying and evaluating indicators for the resource categories. The results of applying a preliminary strategy resulted in its modification to be more broadly applicable. This process was and will continue to be recursive.

Adopting a program strategy for identifying and evaluating indicators has helped reveal shortcomings in our understanding of the resource categories and the measurements needed to understand their condition. Each EMAP Resource Group has its own perspective - resulting from the awareness of the environmental issues associated with each resource category as well as the way in which each resource has been monitored and studied in the past. Delineating shortcomings in our list is meant to stimulate an active effort to fill the gaps, with assistance from those ecologists who understand how a problem in their resource category of expertise was dealt with previously. The unfilled cells in the matrix presented in Table 11-1, which presents the currently identified research indicators, reflect the current gaps as of the writing of this document.

The final purpose of this report is to set the stage for the next step in furthering the EMAP indicator strategy. As was shown in Figure 2-7 (Section 2.4), the EMAP Resource Groups have reviewed literature on potentially appropriate indicators, and through workshops and an initial peer-review process, they have identified indicators that warrant in-depth data analysis and subsequent demonstration in limited-scale field projects.

The next step in the strategy is evaluation of existing data. It is unlikely that many regional data sets exist that are derived from probability sampling of the proposed indicators. In many cases, however, data collected from nonprobability-based networks that use standardized protocols may be useful in establishing components of sampling variance, both among sites and within and among years. EMAP scientists are particularly interested in being made aware of such data sets, because anything that can be done prior to initiating limited-scale field evaluation will greatly increase the cost-effectiveness of such efforts. Anyone having data or research results that might assist EMAP scientists in such analyses are urged to contact:

EMAP Indicator Coordinator
EPA Environmental Research Laboratory
200 Southwest 35th Street
Corvallis, OR 97333

Following completion and peer review of these exploratory evaluations, EMAP will test the most promising indicators in regional demonstration projects. For these demonstration projects, measurements will be made on a full set of developmental indicators for a resource class by using a probability sample. The probability sample will be based on either the unmodified EMAP Tier 2 design (Section 2.2.3) or special Tier 2 designs needed to better evaluate alternatives for long-term implementation. Each demonstration project will be subject to peer review following completion.

A principal purpose of the demonstration projects is to identify core indicators, that is, those indicators to which EMAP is willing to make a monitoring commitment for at least 20 years. Designation as a core indicator depends upon both the information content of the indicator and its associated logistical feasibility or costs. Because most indicators have not been tested for regional monitoring, it is unlikely that sufficient data exist to carefully evaluate either component. Regional demonstration projects will, however, provide such data.

In addition to the demonstration projects, EMAP will coordinate a research program to identify new indicators for potential field testing. This program will include both intramural and extramural expertise, and will focus on filling the gaps in the current understanding of what measurements are needed to quantify ecological condition in the nation's resources and to improve the ability to correlate that condition with patterns and trends in environmental stresses. Early-warning indicators are especially needed, as are better indicators of community structure, indicators of ecosystem processes that can be measured in surveys, animal indicators suitable for regional monitoring, and indices for summarizing information on indicators.

Finally, EMAP must continuously reevaluate its indicator strategy and indicator choices over time, as was shown in Figure 2-7 (Section 2.4). To ensure its long-term survival, EMAP must maintain sufficient stability to continue identifying long-term trends, but at the same time it must avoid succumbing to routine consistency that erodes the program's utility. Iterative evaluation will ensure that EMAP remains a challenging program that is both stable and flexible through the coming decades.

Table 11-1. Research indicators listed by resource category and indicator type. (Codes in parentheses are cross-references to the appendices, where the indicator is discussed in detail.) Indicators in bold have high-priority research status.

RESPONSE	NEAR-COASTAL	INLAND SURFACE WATERS	WETLANDS
Ecosystem Process Rates and Storage	• **Dissolved Oxygen (A.1)** • Biological Sediment Mixing Depth (A.3) • Extent/Density: Submerged Aquatic Vegetation (A.4)	• **Lake Trophic Status (B.1)**	• **Organic Matter/ Sediment Accretion (C.1)** • **Wetland Extent/ Type Diversity (C.2)**
Community Structure	• **Benthic Abundance/ Biomass/ Species Composition (A.2)** • Fish Abundance/Species Composition (A.5)	• **Fish Index of Biotic Integrity (B.2)** • **Macroinvertebrate Assemblage (B.3)** • **Diatom Assemblage in Lake Sediments (B.4)** • **Relative Abundance of Semiaquatic Vertebrates (B.5)**	• **Abundance/ Diversity/ Species Composition: Vegetation (C.3)** • **Relative Abundance: Animals (G1.1)** • Leaf Area/ Solar Transmittance/ Greenness (C.4) • Macroinvertebrate Abundance/ Biomass/ Species Composition (C.5) • Soil/Aquatic Microbial Community Structure (C.6)
Population Structure	• Presence of Large Indigenous Bivalves (A.6)	• **Top Carnivore Index: Fish (B.6)**	• Demographics: Animals (G1.2) • Morphological Asymmetry: Animals (G1.3)
Pathology	• Gross Pathology: Fish (A.7)	• **External Pathology: Fish (B.7)**	

Table 11-1. (Continued)

RESPONSE	FORESTS	ARID LANDS	AGROECOSYSTEMS
Ecosystem Process Rates and Storage	• Nitrogen Export (D.3) • Litter Dynamics (D.4) • Microbial Biomass/ Respiration in Soils (D.5)	• **Vegetation Biomass (E.1)** • **Riparian Extent (E.2)** • **Energy Balance (E.3)** • **Water Balance (E.4)** • **Soil Erosion (E.5)** • **Charcoal Record (E.6)**	• **Nutrient Budgets (F.1)** • **Soil Erosion (F.2)** • **Microbial Biomass in Soils (F.3)** • **Land Use/ Extent of Noncrop Vegetation (F.4)**
Community Structure	• **Relative Abundance: Animals (G1.1)** • Abundance/Species Composition of Understory Vegetation (C.3)	• **Species Composition/ Ecotone Location of Vegetation (E.7)** • **Relative Abundance: Animals (G1.1)** • Abundance/Species Composition of Lichens/ Cryptogamic Crusts (E.8)	• **Relative Abundance: Animals (G1.1)**
Population Structure	• **Tree Growth Efficiency (D.1)** • Demographics: Animals (G1.2) • Morphological Asymmetry: Animals (G1.3)	• **Dendrochronology: Trees and Shrubs (E.8)** • **Pollen Record (E.9)** • **Woodrat Midden Record (E.10)** • Demographics: Animals (G1.2) • Morphological Asymmetry: Animals (G1.3)	• **Crop Yield (F.5)** • **Livestock Production (F.6)** • Demographics: Animals (G1.2) • Morphological Asymmetry: Animals (G1.3)
Pathology	• **Visual Symptoms of Foliar Damage: Trees (D.2)**		• **Visual Symptoms of Foliar Damage: Crops (F.7)**

Table 11-1. (Continued)

EXPOSURE/ HABITAT	NEAR-COASTAL	INLAND SURFACE WATERS	WETLANDS
Biomarkers	• DNA Alteration (G2.1 - G2.3) • Cholinesterase Levels (G2.4) • Metabolites of Xenobiotic Chemicals (G2.5) • Porphyrin Accumulation (G2.6) • Histopathologic Alterations (G2.7) • Macrophage Phagocytotic Activity (G2.8) • Blood Chemistry (G2.9) • Cytochrome P-450 Monooxygenase System (G2.10) • Enzyme-Altered Foci (G2.11)	• DNA Alteration: (G2.1 - G2.3) • Cholinesterase Levels (G2.4) • Metabolites of Xenobiotic Chemicals (G2.5) • Porphyrin Accumulation (G2.6) • Histopathologic Alterations (G2.7) • Macrophage Phagocytotic Activity (G2.8) • Blood Chemistry (G2.9) • Cytochrome P-450 Monooxygenase System (G2.10) • Enzyme-Altered Foci (G2.11)	• DNA Alteration: (G2.1 - G2.3) • Cholinesterase Levels (G2.4) • Metabolites of Xenobiotic Chemicals (G2.5) • Porphyrin Accumulation (G2.6) • Histopathologic Alterations (G2.7) • Macrophage Phagocytotic Activity (G2.8) • Blood Chemistry (G2.9) • Cytochrome P-450 Monooxygenase System (G2.10) • Enzyme-Altered Foci (G2.11)
Pathogens		• Water-Column Bacteria (B.12)	
Bioassays	• **Acute Sediment Toxicity (A.8)** • Water Column Toxicity (A.11)	• **Water-Column/ Sediment Toxicity (B.8)**	•Bioassays (C.10)
Tissue Concentrations	• Chemical Contaminants in Fish/ Shellfish (A.12)	• **Chemical Contaminants in Fish (B.9)**	• Chemical Contaminants in Tissues (C.11)
Ambient Concentrations	• **Chemical Contaminants in Sediments (A.9)** • **Water Clarity (A.10)** • Dissolved Oxygen (A.13)	• **Routine Water Chemistry (B.10)** • Heavy Metals/Man-made Organics (Toxics) (B.13)	• **Nutrients in Water/ Sediments (C.7)** • **Chemical Contaminants in Water/ Sediments (C.8)**
Exotics-GEOs			
Habitat	• Extent/ Density of Submerged Aquatic Vegetation (A.4)	• **Physical Habitat Quality (B.11)**	• **Hydroperiod (C.9)** • **Abundance/ Density of Key Physical Features (G3.1)** • **Linear Classification/ Physical Structure of Habitat (G3.2)**
Landscape			• **Habitat Proportions (Cover Types) (G3.3)** • **Patch Size/Perimeter to Area Ratio (G3.4)** • **Fractal Dimension (G3.5)** • **Contagion/Habitat Patchiness (G3.6)** • Gamma Index of Network Connectivity (G3.7) • Patton's Diversity Index (G3.8)

Table 11-1. (Continued)

EXPOSURE/ HABITAT	FORESTS	ARID LANDS	AGROECOSYSTEMS
Biomarkers	• Stable Isotopes (D.9) • Carbohydrates/Secondary Chemicals: Trees (D.10) • DNA Alteration (G2.1 - G2.3) • Cholinesterase Levels (G2.4) • Metabolites of Xenobiotic Chemicals (G2.5) • Porphyrin Accum. (G2.6) • Histopathologic Alter. (G2.7) • Macrophage Phagocytotic Activity (G2.8) • Blood Chemistry (G2.9) • Cytochrome P-450 Monooxygenase System (G2.10) • Enzyme-Altered Foci (G2.11)	• DNA Alteration (G2.1 - G2.3) • Cholinesterase Levels (G2.4) • Metabolites of Xenobiotic Chemicals (G2.5) • Porphyrin Accumulation (G2.6) • Histopathologic Alterations (G2.7) • Macrophage Phagocytotic Activity (G2.8) • Blood Chemistry (G2.9) • Cytochrome P-450 Monooxygenase System (G2.10) • Enzyme-Altered Foci (G2.11)	• DNA Alteration (G2.1 - G2.3) • Cholinesterase Levels (G2.4) • Metabolites of Xenobiotic Chemicals (G2.5) • Porphyrin Accumulation (G2.6) • Histopathologic Alterations (G2.7) • Macrophage Phagocytotic Activity (G2.8) • Blood Chemistry (G2.9) • Cytochrome P-450 Monooxygenase System (G2.10) • Enzyme-Altered Foci (G2.11)
Pathogens	• Visual Symptoms of Foliar Damage: Trees (D.2)		• Visual Symptoms of Foliar Damage: Crops (F.7) • Agricultural Pest Density (F.8)
Bioassays	• Bioassays: Mosses and Lichens (D.11)		• Lichens/ Mosses/ Clover/ Earthworm Bioassays (F.9)
Tissue Concentrations	• Nutrients in Tree Foliage (D.6) • Chemical Contaminants in Tree Foliage (D.7)	• Foliar Chemistry (E.12)	
Ambient Concentrations	• Soil Productivity Index (D.8)	• Physiochemical Soil Factors (E.13) • Chemical Contaminants in Wood (E.18)	• Quantity/Quality of Irrigation Waters (F.10) • Soil Productivity Index (F.11)
Exotics-GEOs		• Exotic Plants (E.14) • Livestock Grazing (E.15)	
Habitat	• Abundance/Density of Key Physical Features (G3.1) • Linear Classification and Physical Structure of Habitat (G3.2)	• Riparian Extent (E.2) • Fire Regime (E.16) • Mechanical Disturbance of Soils and Vegetation (E.17) • Abundance/Density of Key Physical Features (G3.1) • Linear Classification and Physical Structure of Habitat (G3.2)	• Land Use/Extent of Noncrop Vegetation (F.4) • Abundance/Density of Key Physical Features (G3.1) • Linear Classification and Physical Structure of Habitat (G3.2)
Landscape	• Habitat Proportions (Cover Types) (G3.3) • Patch Size/Perimeter to Area Ratio (G3.4) • Fractal Dimension (G3.5) • Contagion/Habitat Patchiness (G3.6) • Gamma Index of Network Connectivity (G3.7) • Patton's Diversity Index (G3.8)	• Habitat Proportions (Cover Types) (G3.3) • Patch Size/Perimeter to Area Ratio (G3.4) • Fractal Dimension (G3.5) • Contagion/Habitat Patchiness (G3.6) • Gamma Index of Network Connectivity (G3.7) • Patton's Diversity Index (G3.8)	• Habitat Proportions (Cover Types) (G3.3) • Patch Size/Perimeter to Area Ratio (G3.4) • Fractal Dimension (G3.5) • Contagion/Habitat Patchiness (G3.6) • Gamma Index of Network Connectivity (G3.7) • Patton's Diversity Index (G3.8)

Table 11-1. (Continued)

ATMOSPHERIC STRESSORS	ALL RESOURCE CATEGORIES
Chemical	• **Ozone (H.1)** • **Sulfur Dioxide (H.2)** • **Nitric Acid (H.3)** • **Ionic Constituents in Precipitation (H.4)** • Metals and Organics (Toxins) (H.5) • Free Radicals (H.6) • Carbon Dioxide (H.7) • Other Greenhouse Gases (H.8)
Physical	• Ultraviolet Type B Radiation (H.9) • Airborne Particles (H.10)
Biological	

APPENDIX A: INDICATOR FACT SHEETS FOR NEAR-COASTAL WATERS

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A.1 INDICATOR: Dissolved Oxygen

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: High-Priority Research

APPLICATION: The dissolved oxygen (DO) indicator is designed to provide data on estuarine ecosystem processes as they affect water quality and on the habitability of estuarine waters for marine life, including economically important resources. Because these data needs are different, this fact sheet addresses DO as an indicator of near-coastal ecosystem processes, whereas fact sheet A.13 addresses DO as an exposure indicator of anoxic conditions to marine life. The assessment endpoint is extent of eutrophication because wide fluctuations in DO often result from increased primary productivity due to nutrient enrichment and can often lead to hypoxia. In a technical sense, DO is a prime physical indicator of estuarine ecosystem processes because (1) DO concentrations may reflect prior nutrient loading and (2) anaerobic conditions and may lead to the formation of anaerobic sediments and/or H_2S (a highly toxic compound), which affects biogeochemical cycling of essential elements (e.g., remineralization of toxicants). Although causes of changes in the concentration of DO are complex, the ability to make meaningful measurements is readily available.

INDEX PERIOD: Water column profiles of DO would be measured from mid-June to September. This period was chosen because of the elevated temperatures, low riverine flow conditions, and low DO conditions known to exist at this time.

MEASUREMENTS: Water column profiles of DO would be measured at least six times at each location. The method of choice is a system that employs a polarographic oxygen probe (Gnaiger 1983) manufactured by Sea Bird Electronics, Inc., that utilizes a plastic membrane on the sensor and is equipped with a data logger. Calibration is completed by Winkler titration, and air calibration checks are used as a backup method. The capital cost for the conductivity, temperature, and DO unit is approximately $30,000. Two mid-level field technicians can calibrate, deploy, and download data in about 1 h. For six deployments, about 12 person-hours are required. The recommended interannual sampling frequency would be every year.

It is difficult to assess all aspects of uncertainty that can influence measurement error; for example, all relevant sensors (pressure transducer, conductivity cell, and thermistor) must provide usable data. A field calibration for accuracy, precision, and reliability would be required. The computed resolution of the Sea Bird system is 0.01 ppm, and accuracy is stated by the manufacturer to be ±0.2 ppm. DO saturation estimates include uncertainties in the thermistor and conductivity sensors.

VARIABILITY: The spatial variability within an estuarine sampling unit is expected to yield coefficients of variation of approximately 100%. The expected temporal variability of DO during the index period would produce a range from 0 to 7-10 ppm.

PRIMARY PROBLEMS: The question of representativeness of the data is of concern. The index period is subject to several processes that may cause the low oxygen "event" to be missed in one or more estuaries. It is expected that the method of single point measurements that are spread out over the index period would identify sites consistently experiencing low DO. The EMAP Near-Coastal demonstration project during summer 1990 will provide critical information regarding the suitability of the sampling design.

REFERENCES:

Gnaiger, E. 1983. In situ measurement of oxygen profiles in lakes: Microstratifications, oscillations, and the limits of comparison with chemical methods. Pages 245-264. In: E. Gnaiger and H. Forstner, eds. Polarographic Oxygen Sensors, Springer-Verlag, New York.

A.2 INDICATOR: Benthic Abundance, Biomass, and Species Composition

CATEGORY: Response/ Community Structure

STATUS: High-Priority Research

APPLICATION: Estuarine benthic organisms are preferred prey of many fish and crabs, and as such, form key intermediate linkages between higher and lower trophic levels. Their burrowing and feeding activities have important effects on oxygen, nutrient, carbon, and mineral cycling, including the sequestering and cycling of contaminants. Most benthic organisms are immobile and cannot avoid changes in environmental conditions that occur at a site. Immobility makes benthic assemblages relatively easy to sample and the data that are collected straightforward to interpret. The responses of benthic organisms to anthropogenic stress and natural environmental changes are relatively well understood and include not only changes in population size and diversity but also changes in growth rate, age-class composition, and recruitment success. As a result, benthic population and community characteristics including abundance, biomass, and species composition are sensitive indicators of contaminant and dissolved oxygen stress and serve as good integrators of estuarine environmental quality.

INDEX PERIOD: Benthic abundance and species composition data would be collected during summer (mid-June to September), the period when benthic exposure to stressful, low dissolved oxygen concentrations associated with eutrophication is most likely to occur. In addition, the effects of contaminant exposure are likely to be most severe at the high temperatures that occur during this time period. Major recruitment and mortality for most dominant species should occur prior to the designated sampling period, and most benthic populations should also be relatively stable during this period.

MEASUREMENTS: Three 200-cm^2 box cores of bottom sediments would be collected at each station and sieved through a 0.5-mm screen. All taxa collected would be identified and counted to the lowest taxonomic level practical. The biomass of regionally dominant species would be estimated as wet biomass. Methods would generally follow those of Holme and McIntyre (1971) and Holland et al. (1987). The estimated capital equipment cost for the grab sampler and the sieves is $2000. Three mid-level field technicians can deploy the grab three times and sieve and package the samples in about 1 h. The cost of processing all samples from each station is $400, and the measurement error is estimated at 10-20% The recommended interannual sampling frequency would be every year.

VARIABILITY: The major sources of variation in benthic population and community characteristics include fluctuations associated with variation in sediment characteristics and salinity. Samples would be collected for all major salinity strata. The influence of variation in sediment characteristics on benthic abundance would be accounted for by making appropriate adjustments to the benthic data based on the data collected on sediment characteristics. The spatial variability of benthic diversity and biomass estimates within estuarine sampling units are expected to have a coefficient of variation (CV) <50%, after normalization for sediment characteristics. Temporal variability during the index period is expected to be minimal (CV < 30%).

PRIMARY PROBLEMS: The identification of all taxa to the species level would be time-consuming and expensive. The required level of taxonomic identification would be evaluated as part of the Virginian Province Demonstration Project in summer 1990. The sample design assumes that the seasonal periodicity for dominant populations would be similar throughout the study region and that variation in benthic stock size and community characteristics due to variation in sediment characteristics and salinity can be quantified by using conventional parametric statistical methods (e.g., regression analysis). The validity of these assumptions would also be tested in the demonstration project. Results of evaluating available data suggest they are reasonable assumptions.

REFERENCES:

Holland, A.F., A.T. Shaughnessy, and M.H. Hiegel. 1987. Long-term variation in mesohaline Chesapeake Bay: Spatial and temporal patterns. Estuaries 10:227-245.

Holme, N.A., and A.D. McIntyre. 1971. Methods for Study of Marine Benthos. Blackwell Scientific Publications., Oxford, England.

A.3 INDICATOR: Biological Sediment Mixing Depth

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: Research

APPLICATION: The proposed benthic indicators were selected to allow the assessment of the benthic condition. The condition of the benthic environment is important because the benthos are (1) a food resource for important finfisheries, (2) consumers of a significant proportion of primary production, (3) sediment *processors* capable of controlling nutrient and contaminant sediment fluxes, (4) sensitive indicators of contaminant- and eutrophication-induced hypoxic acute stresses, (5) determinants of habitat structure, and (6) indicators of cumulative anthropogenic stress. Biological mixing depth directly relates to the ability of the benthos to distribute and oxidize sediments and is generally negatively correlated with both physical and anthropogenically induced disturbance. The biological mixing depth in fine-grained sediments indicates the types, sizes, and activities of the resident fauna. Chemical contamination of the sediments often inhibits burrowing activities of "conveyer-belt" forms, thereby inhibiting natural sediment processing. More resistant, short-lived species are able to maintain a shallow mixed zone near the sediment-water interface.

Under enrichment conditions, resulting from proximity to sewage outfalls or detrital fallout from algal blooms, increased demands of the sediment for oxygen can exclude both long-lived and short-lived species, which will cause a depression of the mixing depth, migration of the oxic-anoxic sediment boundary (redox potential discontinuity) toward the sediment-water interface, and the scavenging of oxygen from near-bottom waters.

INDEX PERIOD: The sampling period should occur when biological activity is at a maximum, which is usually at peak summer temperatures. Recruitment to the benthic community tends to occur before and during this index period, which is also the most likely time frame for hypoxic events. Stress effects occurring at this time would likely have significant effects on the structure of the benthos through adult mortality and by altering normal recruitment patterns.

MEASUREMENTS: Biological mixing depth data are collected with a benthic interface camera (Rhoads and Germano 1982, 1986), which photographs the sediment-water interface in the vertical. The photograph is then processed by image analysis to quantify mixing depth and grain size. Presence and abundance of surface tube structures, boundary roughness, penetration depth, and presence of feeding voids and methane gas can also be detected by this analysis. The ease of sampling allows this method to be used for large-scale characterization and mapping. Measurement error in the mixing depth estimation is typically 0.1 to 0.3 cm, and changes of 0.5 cm have been shown to be statistically significant. The capital cost for the initial design and lease of the lightweight camera is $30,000. Sampling requires two mid-level technicians for 0.5 h at each station within an estuarine sampling unit, and image processing can be accomplished for $50 per image.

A natural summer-winter cycle occurs in the vertical extent of the mixing depth that is related to temperature and driven by biological activity in the benthos. Therefore, these measurements should be made with the same interannual frequency as those for benthic communities.

VARIABILITY: Because the mixing depth is related to the composition, abundance, and activity of the infauna, the same factors controlling regional variability of these indicators are operable. The spatial variability of mixing depths within an estuarine sampling unit is expected to produce coefficients of variation (CV) in the range of 50 to 100%. The expected temporal variability of mixing depth during the index period is also expected to be of the same magnitude, that is, CV < 30%.

PRIMARY PROBLEMS: The strengths of this indicator include ease of sampling, rapid data turnaround (<30 days), and a functional approach to benthic processes. Its primary weakness is that the sediment-organism process paradigm has not been fully tested in low-saline and freshwater habitats. For immediate implementation in EMAP, a lightweight version (<80 kg, or 200 lb) of the camera would have to be designed, fabricated, and tested; the design, materials, and vendors have been identified.

REFERENCES:

Rhoads, D.C., and J.D. Germano. 1982. Characterization of organism-sediment relations using sediment profile imaging: An efficient method of remote ecological monitoring of the seafloor (REMOTS system). Mar. Ecol. Prog. Ser. 8:115-128.

Rhoads, D.C., and J.D. Germano. 1986. Interpreting long-term changes in benthic community structure: A new protocol. Hydrobiologia 142:291-308

A.4 INDICATOR: Extent and Density of Submerged Aquatic Vegetation

CATEGORY: Response/ Ecosystem Process Rates and Storage
Exposure and Habitat/ Habitat

STATUS: Research

APPLICATION: Submerged aquatic vegetation (SAV) beds provide important spawning and nursery habitats for fish and crabs by providing cover, protection, and a food source. SAV also reduces currents and baffles waves, which creates a depositional environment and improves water quality. The root systems of SAV stabilize sediments. Changes in environmental conditions associated with eutrophication and increases in suspended sediment concentrations adversely affect SAV by reducing the amount of light that reaches submerged stems and leaves. SAV are also adversely affected by excessive use of herbicides. A positive correlation generally exists between SAV acreage and the abundance of commercially and recreationally important fish and crabs. SAV acreage is therefore a good indicator of estuarine water quality and "health." Furthermore, the recent increased understanding of environmental requirements for SAV has assisted in the interpretation of SAV data. Scientists can better separate changes due to natural processes from changes due to pollution stress.

INDEX PERIOD: Sampling would be conducted in the August-September period of the water column when peak biomass of SAV occurs.

MEASUREMENTS: SAV bed outlines and density (areal cover classes) would be digitized from normal-color aerial photography (conventional mapping camera). Factors to be considered when scheduling overflights include tidal stage, time of day, sun angle, wind, turbidity, and atmospheric conditions. Digitized data would be used to estimate SAV acreage and bed density within sampling strata and within the region as a whole. This indicator could be monitored in the Virginian Province (Cape Hatteras to Cape Cod) for $250K per year. The recommended interannual sampling frequency would be five years.

VARIABILITY: The expected spatial and temporal variability of SAV areal extent and bed density within an estuarine sampling unit and during an index period, respectively, were not estimated because sufficient data are unavailable.

PRIMARY PROBLEMS: Because image acquisition is limited by season, tidal conditions, atmospheric conditions, and other requirements, acquiring the needed data would be difficult.

BIBLIOGRAPHY:

Orth, R., J. Simmons, J. Capelli, V. Carter, L. Hindman, S. Hodges, K. Moore, and N. Ribicki. 1985. Distribution of submerged aquatic vegetation in the Chesapeake Bay and tributaries. U.S. Environmental Protection Agency/Virginia Institute of Marine Sciences Joint Publication, Annapolis, MD.

Stevenson, J.C. 1988. Comparative ecology of submersed grass beds in freshwater, estuarine, and marine environments. Limnol. Oceanogr. 33:867-893.

A.5 INDICATOR: Fish Abundance and Species Composition

CATEGORY: Response/ Community Structure

STATUS: Research

APPLICATION: One of the principal means by which the public assesses the environmental quality of estuaries is by the quality and abundance of the fish assemblage. Although community measures of the estuarine fish have not yet been well established, the concept is based on a simple pretext. There is a societal concern on the diversity of the fish community outright, as well as on how that diversity contributes to ecosystem sustainability. Species assemblages reflect the cumulative impact of water quality parameters, contaminant inputs, and habitat conditions. While abundance and species composition may not be very sensitive to small stresses, assemblages dominated by tolerant species such as mummichogs and carp, or locations where little or no fish are captured, can be identified as subnominal. Species assemblage measurements have the advantage of adding only a trivial incremental cost for its measurement, since trawling is already being accomplished to gather fish for contaminant and pathogen analyses, and all community measures can be made in the field.

INDEX PERIOD: Fish trawls will be conducted from June to September. This is the time of year that many marine species of fish utilize the estuaries for nursery and spawning habitat; catch probabilities, as a result, will be enhanced. This also is the time of year that the potential for stress effects due to low dissolved oxygen is greatest.

MEASUREMENTS: Fish would be collected with a 12-m (40-ft) otter trawl deployed for 10 min against the tide. Trawling operations would be standardized to allow the comparison of catch data. Three quantitative collections would be conducted at each estuarine sampling unit at approximately one-month intervals during the index period. From these collections, all taxa would be enumerated, and lengths would be measured for the first 30 individuals of each target taxa. Capital cost for the otter trawl is $1600. The trawling operation will take three mid-level field technicians 1.5 h each to deploy, sort, and enumerate the samples. Data entry adds another 2 h. Trawling three times requires a total of 20 person-hours at each station within an estuarine sampling unit. The recommended interannual sampling frequency would be every year.

VARIABILITY: The expected temporal variability in species abundance of estuarine fishes during the index period would produce ranges that deviate >100% from the mean value. Many, though not all, estuarine fish inhabit different parts of the estuary at different periods during the summer. Having information to composite from three different summer sampling periods should reduce the annual temporal variability; however, considerable small-scale temporal variability and spatial variability would still remain. Because of microhabitat differences that are not apparent from the water surface, the expected spatial variability of species assemblages within an estuarine sampling unit would produce a range that deviates >100% from the mean value during each period at a subset of the sampling stations.

PRIMARY PROBLEMS: The analytical methods for this indicator still require some development. Some simple measurements, such as average biomass of fish caught in the three quantitative trawling operations and the proportion of tolerant species, are likely candidates; however, more refined methods are being developed. An approach is being developed that allows definition of desirable species expected at a station, based on a variety of physical characteristics such as salinity, temperature, bottom type, and latitude. Catch probabilities for a number of species have been calculated from existing trawling data. The EMAP Near-Coastal Demonstration Project will provide the data necessary to determine expected species. With this approach, a nominal condition would be defined by the fraction of these expected taxa that are caught at a station. Another alternative is an integrative approach, such as the Index of Biotic Integrity (IBI), that combines numerous measures, such as species composition, abundance, and gross pathology, into a single value. The IBI has been successfully applied in the freshwater environment and would be used as an indicator for inland surface waters (see indicator B.2) but still needs to be adapted for application in the estuarine environment.

BIBLIOGRAPHY:

Wedemyer, G.A., D.J. McLeay, and C.P. Goodyear. 1984. Assessing the tolerance of fish and fish populations to environmental stress: The problems and methods of monitoring. Pages 163-195. In: V.W. Cairns, P.V. Hodson, and J.O. Nriagu, eds. Contaminant Effects on Fisheries, John Wiley and Sons, New York.

Goodyear, C.P. 1983. Measuring effects of contaminant stress on fish populations. Pages 414-424. In: W.E. Bishop, R.D. Cardwell, and B.B. Heidolph, eds. Aquatic Toxicology and Hazard Assessment, Sixth Symposium. ASTM STP 802. American Society for Testing and Materials, Philadelphia.

A.6 INDICATOR: Presence of Large Indigenous Bivalves

CATEGORY: Response/ Populations

STATUS: Research

APPLICATION: Estuarine waters serve as nursery grounds to many economically important species. Observed reductions in commercial and recreational catches of numerous taxa have been attributed to anthropogenic inputs (U.S. OTA 1987). Shellfish productivity is a meaningful indicator because shellfish are economically important as a commercial and recreational resource, and the presence of shellfish suggests that water and sediment quality conditions are acceptable for other activities such as swimming or fishing (Franz 1982). The use of indigenous filter-feeding shellfish for contaminant measurements (see indicator A.12) also provides a good indication of site-specific water column exposures to chemical pollutants because these organisms are relatively immobile.

INDEX PERIOD: This indicator can be measured at any time of the year because the abundance of these organisms over a certain size range does not fluctuate greatly.

MEASUREMENTS: Infaunal bivalves would be collected using a rocking chair dredge, then enumerated and identified to the species level. The data would be presented as the fraction of estuarine habitat that supports infaunal bivalve populations. Up to 10 selected target species would be measured to provide an indication of the relative age structure of the population. Selected species would also be archived for chemical analyses. The rocking chair dredges cost $1500 apiece. The dredge can be deployed and the sample sorted and enumerated by three mid-level field technicians in approximately 1.5 h. The recommended interannual sampling frequency would be three to five years.

VARIABILITY: The temporal variability of a bivalve species' presence during the index period is expected to be low (<30%) because these are long-lived organisms. The spatial variability of a bivalve species' presence within an estuarine sampling unit was not estimated because data of this nature is unavailable.

PRIMARY PROBLEMS: Relatively few problems are associated with data collection; use of the sampling apparatus is straightforward, and most data will be generated in the field.

REFERENCES:

U.S. OTA. 1987. Wastes in marine environments. U.S. Office of Technology Assessment, Government Printing Office, Washington, DC.

Franz, D.R. 1982. An historical perspective on mollusks in lower New York Harbor, with emphasis on oysters. Pages 187-197. In: G.F. Mayer, ed. Ecological Stress and the New York Bight: Science and Management. Estuarine Research Federation, Columbia, SC.

A.7 INDICATOR: Gross Pathology: Fish

CATEGORY: Response/ Pathology

STATUS: Research

APPLICATION: Gross pathology of finfish from estuarine waters provides an evaluation of finfish health, which reflects estuarine condition. In contaminated aquatic environments, finfish are known to develop a number of readily observed pathologic changes. Some are easily noted through external examination, including the occurrence of lesions such as fin rot, skin ulcerations, some skeletal abnormalities, and epidermal growths. Gross examination of internal organs can provide additional (and possibly more valuable) information because many pathologic conditions, including various tumor types and certain parasitic infections, may be easily observed through gross internal examination but provide no external indications of their presence. In addition, pathological condition in finfish may provide an indication of health risks to larger population groups (e.g., avian, mammalian, human) that utilize the same systems for food sources and recreation. Therefore, this indicator should be of interest to all resource and regulatory agencies, as well as the general public.

INDEX PERIOD: An optimal sampling period for measuring gross pathology is during the warmer months of the year, because biological systems respond directly to temperature. The disease conditions that are easily detectable by gross examination, such as fin rot and lymphocystis, are known to occur more often during the spring and summer months.

MEASUREMENTS: Fish would be collected three times during the index period by using an otter trawl. A gross examination would be conducted on at least three target finfish species collected at each station by using the methods of Amlacher (1970) and Couch (1985). The examination would consist of a thorough external inspection of the fins, eyes, body surfaces, branchial chamber, and buccal cavity. Additionally, a midline incision would be made in the ventral abdomen to observe the visceral organs and to perform a thorough gross internal examination. Various pathologic changes would be noted, and tissue would be taken from any suspect or unidentifiable internal or external lesions and fixed in 10% neutral buffered formalin. The pathology indicator can be measured from the same trawling collections used to measure fish abundance and composition (see indicator A.5). An additional 1 to 2 h of a mid-level field technician is required to document the pathologies. Verification of these observations by expert pathologists costs about $200 at each station within an estuarine sampling unit.

One potential source of measurement error is associated with the individuals conducting gross examinations. Because multiple teams will be collecting data and assessing fish pathology simultaneously, it is imperative that adequate training be provided to all teams prior to sampling in order to ensure uniform characterization. Because the natural interannual variability is unknown, annual sampling would be required.

VARIABILITY: The expected spatial and temporal variabilities in the incidence of gross pathologies within an estuarine sampling unit and during the index period, respectively, are unknown and were not estimated.

PRIMARY PROBLEMS: In addition to the experience factor noted above, the representativeness of the collections is a concern. The stability in the response of this indicator would be evaluated by comparing the three separate collections to the combined data. If large enough numbers of finfish are carefully examined from each sampling unit, some information concerning their health status can be obtained.

REFERENCES:

Amlacher, E. 1970. Textbook of Fish Diseases. T.H.F. Publications, New Jersey.

Sinderman, C.J. 1979. Pollution-associated diseases and abnormalities of fish and shellfish. Fish. Bull. 76:717-749.

Couch, J.A. 1985. Prospective study of infectious and non-infectious diseases in oysters and fishes in three Gulf of Mexico estuaries. Dis. Aquat. Org. 1:59-82.

A.8 INDICATOR: Acute Sediment Toxicity

CATEGORY: Exposure-Habitat/ Bioassays

STATUS: High-Priority Research

APPLICATION: The response indicators affected by sediment toxicity are benthic community structure, community function, and population dynamics. Benthic assemblages represent ecologically and economically important resources whose protection is mandated by a variety of EPA regulations (e.g., Ocean Dumping, 301[h], 404[c]). Also, degradation of benthic productivity adversely affects other segments of the marine ecosystem, especially demersal fishes. Benthic toxicity results from the bioaccumulation of chemicals in sediments (e.g., metals, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, chlorinated hydrocarbons). Toxic sediments promote the degradation or complete elimination of sensitive benthic species. As the sediments become increasingly toxic, the natural benthic community is replaced by a depauperate assemblage of stress-tolerant species. The replacement of species often results in a reduction in diversity, loss of preferred demersal fish prey (e.g., phoxocephalid and ampeliscid amphipods), and appearance of opportunistic species (e.g., *Capitella capitata*).

INDEX PERIOD: No critical sampling period for this indicator is known; therefore, sampling may occur at any time of the year.

MEASUREMENTS: The sediment toxicity indicator is based on laboratory bioassays of field-collected sediment. Acute response criteria based typically on 10-day bioassays for benthos are mortality, emergence from toxic sediment, and behavioral effects (e.g., inability to rebury in clean sediments). Several standard methods exist for acute sediment toxicity tests (Swartz et al. 1985). The American Society for Testing and Materials is currently developing standard guidelines for both marine and freshwater amphipod sediment bioassays. For a typical experimental or survey design, these procedures specify the collection of 200 mL of sediment from each of three to five replicate grab samples at each station. The bioassays are conducted for 10 days under static conditions at constant temperature and salinity. The amphipods *Ampelisca abdita, Rhepoxynius abronius, Rhepoxynius hudsoni, Eohaustorius estuaries, Hyalella azteca, and Grandidierella japonica* have been used in acute sediment bioassays. With five replicates, the amphipod procedure can detect statistically significant increases in mortality of about 20% in comparison with a control group. Sediments for this indicator can be collected by using the same gear and crew as for the benthic community measurements (see indicator A.2). An additional four grabs are required, which take two mid-level field technicians 45 to 60 min to collect, composite, and package for shipment. The cost of the toxicity tests is $500-$750 per sample, depending on the species. The expected spatial variability of sediment toxicity within an estuarine sampling unit would produce a range that deviates >100% of the mean value (Long and Buchman 1989).

Because long-term transport and geochemical processes generally control sediment contamination, temporal changes in sediment toxicity can be monitored at infrequent intervals. The interannual sampling frequency therefore would be three to five years.

VARIABILITY: Detection of temporal or spatial differences in toxicity will be a function of the heterogeneity of contaminant concentrations in the collected sediments and system-specific particle deposition rates. The expected temporal variability of sediment toxicity throughout the year would produce a range that deviates <10% of the mean value.

PRIMARY PROBLEMS: Acute sediment toxicity is not an early-warning indicator of benthic degradation. Toxicity usually occurs only after substantial chemical contamination of the seabed. The development and application of chronic and sublethal test methods with whole organisms are critical to the identification of habitats experiencing sublethal impacts.

REFERENCES:

Long, E.R., and M.F. Buchman. 1989. An evaluation of candidate measures of biological effects for the National Status and Trends Program. Technical Memorandum NOS OMA 45. U.S. National Oceanographic and Atmospheric Administration, Rockville, MD.

Swartz, R.C., W.A. DeBen, J.K.P. Jones, J.O. Lamberson, and F.A. Cole. 1985. Phoxocephalid amphipod bioassay for marine sediment. Pages 152-175. In: R.D. Cardwell, R. Purdy, and R.C. Bahner, eds. ASTM STP 865. American Society for Testing and Materials, Philadelphia, PA.

A.9 INDICATOR: Chemical Contaminants in Sediments

CATEGORY: Exposure-Habitat/ Ambient Concentrations

STATUS: High-Priority Research

APPLICATION: The endpoint of concern is the chemical contamination of the marine ecosystem, particularly the potential ecological effects of those contaminants sequestered in sediments. Bottom sediments in some industrialized and urban harbors have become so contaminated that they represent a threat to both human and ecological health. Contamination, however, is not limited to these urban/industrial centers; pollutant runoff from agricultural areas is also an important source of contaminant input to estuaries. The geographic extent of contaminated sediments and the ecological exposure to them is largely unknown, even in contaminated industrial areas. This information is necessary in order to assess the effectiveness of pollution abatement programs.

INDEX PERIOD: Sampling for chemical contaminants in sediments would occur in the summer index period to be concurrent with other indicator measurements. There is no reason, however, that they could not be sampled at any other time of the year.

MEASUREMENTS: Surface sediments (top 2 cm) would be collected and composited from several box cores from each station within an estuarine sampling unit. The constituents to be measured would be the same as those measured by the National Oceanic and Atmospheric Administration's National Status and Trends (NS&T) program. These compounds include chlorinated pesticides, polychlorinated biphenyls, polyaromatic hydrocarbons, major elements, and toxic metals. Coprostanol and *Clostridium* spores would be measured as indicators of sewage loading. Total organic carbon and grain size would also be quantified. Sediment samples for this indicator can be collected by using the same gear and crew as for the benthic community measurements (see indicator A.2). An additional two grabs are required, which take two mid-level field technicians approximately 30 min to collect, composite and package for shipment. The chemical analyses can be conducted for about $1000 per sample. As noted for sediment toxicity (see indicator A.8), long-term transport and geochemical processes control sediment contamination, and a three- to five-year interannual sampling frequency would be adequate to detect significant contaminant trends. NS&T data would be evaluated to confirm the appropriate sampling frequency.

The major source of measurement variability for this indicator would occur in sample collection and processing. With adequate standardization of methods, however, this error should be reduced such that coefficients of variation (CV) are <10%.

VARIABILITY: The signal-to-noise ratio, variance, and precision of these data can best be determined through analysis of data collected during the 1990 EMAP - Near-Coastal demonstration project. As noted above, temporal variability during the index period is expected to be small (CV < 10%). Spatial variability has been examined at the NS&T sites for four years of data (U.S. NOAA 1988). The average within-site coefficient of variation for organic contaminants was between 57 and 75%, and for metals the CV was 21 to 69%. These data are normalized for grain size effects.

PRIMARY PROBLEMS: The proposed analytes for the sediment chemistry indicator are well established and described by standard methods or documented programs (e.g., NS&T). As an exposure indicator, the interpretation of these data will suffer from a lack of information on the bioavailability of the contaminants and subsequent ecological effects.

REFERENCE:

U.S. NOAA. 1988. National Status and Trends Program for marine environmental quality. A summary of selected data on chemical contaminants in sediments collected during 1984, 1985, 1986, and 1987. Technical Memorandum NOS OMA 44. National Oceanographic and Atmospheric Administration, Rockville, MD.

A.10 INDICATOR: Water Clarity

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: High-Priority Research

APPLICATION: Water clarity may be the one indicator that is perceived as most indicative of water quality to the public because of the ease in making an instantaneous assessment of this parameter. In the context of EMAP, water clarity is used as an indicator of water quality conditions because decreased clarity (1) may indicate increased nutrient enrichment with consequent decreases in dissolved oxygen (DO) concentrations, (2) impairs light penetration in the water, which may affect the growth of submerged aquatic vegetation, (3) may signal nuisance algal blooms including those indirectly toxic to marine life and humans because they ingest fish products tainted by the algal toxins, (4) may be correlated with fish and shellfish kills, (5) is accompanied by the loss of aesthetic appeal due to reduced visibility, which may affect recreational activities in shallow waters (e.g., recreational crabbing by dip net, scuba diving). Changes in water clarity may also be due to industrial effluent color and turbidity.

INDEX PERIOD: Water clarity would be measured during the June-September sampling period for the same reasons as those for measuring DO (i.e., major algal blooms such as dinoflagellates typically occur during this period).

MEASUREMENTS: Water clarity would be quantified as light transmission by using a Sea Tech transmissometer with a 10-cm path length. This instrument measures the attenuation of light due to absorption or scattering by particles in the water; it would be lowered through the water column to obtain a vertical profile of water clarity. The amount of attenuation is a function of the concentration and characteristics of suspended material in the water column; however, absolute estimates of suspended solids concentrations would not be generated. These data would be used only to provide information on relative light transmission.

In addition to transmissometry, a fluorometry profile would be generated at each station within an estuarine sampling unit to estimate the concentration of chlorophyll a. The fluorometer emits light (425 nm) that excites chlorophyll, which results in an emission at 685 nm. The instrument measures this light emission. Fluorometry and transmissometry together provide a picture of water clarity and the contribution of phytoplankton to turbidity. Capital costs for the transmissometer and fluorometer are $1200, and they can be deployed along with the rest of the conductivity, temperature, and DO package at no extra cost.

VARIABILITY: The major source of variability associated with these measurements is the spatial and temporal variability of suspended solids, including phytoplankton. The expected spatial and temporal variabilities, within an estuarine sampling unit and during the index period respectively, were not estimated because data at this scale was unavailable.

PRIMARY PROBLEMS: As noted above, the primary problem with these measurements would be the effects of changes in suspended particulate type throughout the water column. Different particle types and their resultant light transmission would not be measured consistently using the transmissometer, and thus only relative transmission values would be reported.

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A.11 INDICATOR: Water Column Toxicity

CATEGORY: Exposure and Habitat/ Bioassays

STATUS: Research

APPLICATION: The water column toxicity indicator is designed to provide estimates of the acute and chronic toxicity of ambient near-coastal waters. Water column toxicity in near-coastal waters is considered important because (1) it is widely perceived as one of the most serious near-coastal impacts, (2) most marine and estuarine plants and animals spend at least some portion of their life cycle as water column organisms, especially commercially important larval forms of vertebrates and invertebrates. (3) many of the commercial marine and estuarine species and the organisms that they eat spend most or all of their life cycles in the water column, (4) the public is very concerned about pollutant-induced mortalities and sublethal effects, and (5) there is evidence that such toxicity is widespread in industrialized estuaries. Anthropogenic inputs to many rivers, coastal urban environments, and the atmosphere are likely to eventually reach coastal marine and estuarine waters. In addition, considerable quantities of toxic pollutants are discharged directly to the water column through industrial and municipal effluent, urban runoff, etc.; therefore, water column toxicity from these and other sources may be a significant factor affecting ecological condition.

INDEX PERIOD: The June to September sampling period is appropriate because water quality conditions are expected to be most stable as a result of low runoff and riverine flow, which tend to reduce the pulsed inputs of contaminants. Because of the elevated summer temperature, biological responses to adverse water quality conditions should be more easily detectable.

MEASUREMENTS: The following species and sublethal response parameters have been selected for the near-coastal toxicity indicator: red alga, *Champia parvula* - reproduction (U.S. EPA 1988); sea urchin, *Arbacia punctulata* - reproductive success as percent fertilization (U.S. EPA 1988); bivalve larval test, *Mytilus edulis, Crassostrea virginica* - survival, growth, fertilization (Chapman and Morgan 1983). Standard methods for these tests exist and have been routinely applied in water quality assessments. The data generated from the toxicity tests would consist of absolute values of survivors (all species), number of fertile eggs (sea urchin), and normal shell growth (bivalve larval test). Each test method has a minimum criterion for response under control conditions. A standard reference seawater for the indicator should be established and compared with the monitoring data. The values generated in the monitoring study would be compared with the reference responses, with other values from other sample locations, and with past values from the same station for trend analysis. The water samples could be collected and packaged for shipment by a mid-level field technician in about 1 h. The water grab sampler costs $1000. Samples can be tested for about $900 per station.

An estimate of intertest variability, in the form of coefficients of variation, has recently been completed after a series of precision tests for two of the proposed tests: *C. parvula* (31%) and *A. punctulata* (41%). A recommended interannual sampling frequency was not suggested.

VARIABILITY: The variability associated with these tests on a regional scale will be determined after completion of the demonstration project in 1990. Temporal and spatial variability is related to pollutant discharges, runoff, and riverine discharges. The expected spatial variability of water column toxicity within an estuarine sampling unit would produce a range that deviates up to 100% of the mean value.

PRIMARY PROBLEMS: The most important technical concern with the toxicity indicator is the determination of the most appropriate method for sample compositing which would provide a sample that is representative of the surrounding ambient waters. The main logistical concern associated with the toxicity indicator is the timely delivery of the water samples to one or more central testing facilities. The samples must be collected, shipped at 40°C, and received for testing within a 24-h period. Commercial overnight delivery is a logical option that likely would be used.

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Chapman, P.M., and J.D. Morgan. 1983. Sediment bioassays with oyster larvae. Bull. Environ. Contam. Toxicol. 31:438-444.

A.12 INDICATOR: Chemical Contaminants in Fish and Shellfish

CATEGORY: Exposure and Habitat/ Tissue Concentrations

STATUS: Research

APPLICATION: Thousands of chemical compounds, which are either produced or mobilized by human activities, are released either directly or indirectly to the marine environment; however, most of these compounds are not accumulated by biota. Therefore, selected chemical measurements made on the tissues of fish and shellfish would be used to provide information on the extent of chemical contamination. In addition, detailed analysis of the data for certain less mobile species may provide important information on the sources of contamination. Because the analytical techniques available for measurement of chemical compounds are very sensitive, the results may provide an early warning for emerging problems that could affect the viability of ecological systems. Finally, the presence of chemical contaminants in commercially important marine resources is of concern from a human health perspective.

INDEX PERIOD: The summer sampling period is appropriate because the fish and shellfish would be metabolically active during this period and bioaccumulation rates should be at a maxima. Fish must be collected for sampling during a specific time of the year to minimize seasonal differences.

MEASUREMENTS: Several classes of compounds including polychlorinated biphenyls, chlorinated pesticides, polycyclic aromatic hydrocarbons, and metals have been shown to accumulate in aquatic organisms. Representative compounds from each of these chemical classes should be measured. Those now measured by the National Status and Trends (NS&T) Program of the National Oceanic and Atmospheric Administration (NOAA) would constitute the initial suite of selected compounds (U.S. NOAA 1987). The selection of this chemical suite allows for comparisons with historical data. The results should be reported in units of nanogram- or microgram-per-gram wet weight, dry weight, and lipid weight. The fish and shellfish analyzed for chemical contaminants could be collected by using the same gear and personnel previously described for fish and shellfish indicators (see indicators A.5, A.6) at no additional cost. Chemical analyses would cost $1000 per sample. The recommended interannual sampling frequency would be every year.

The levels of uncertainty associated with the measurement of contaminants in tissues would be specific to the compounds being measured and the methods that are employed. In general, however, the measurement error is likely to be between 10 and 20%.

VARIABILITY: Spatial variability in fish contaminant concentrations within an estuarine sampling unit is expected to be large (>100%) because of the subject's mobility; however, this should not be the case with bivalves. Temporal variability of indigenous bivalves during the index period should yield coefficients of variation that range from 0 to 50%; thus, a synoptic sample would provide reliable estimates of contamination trends. The variability associated with the regional sampling design would be quantified after the 1990 EMAP Near-Coastal Demonstration Project.

PRIMARY PROBLEMS: The overriding technical problem is that many different methods exist that could be used for the measurement of chemical residues in tissues. Differences in analytical methods affect detection limits, information generated, costs, and most importantly, the comparability of data generated by different laboratories. Even if the same method or similar methods are used by different laboratories, large differences can occur in the data that are produced. A strong quality assurance program must be instituted to maximize the comparability of results and should include intercalibration exercises and the use of standard reference materials. The NS&T program has developed an appropriate quality assurance program, in which EMAP plans to participate.

REFERENCES:

U.S. NOAA. 1987. National status and trends program for marine environmental quality, progress report. Technical Memorandum NOS OMA 38. National Oceanographic and Atmospheric Administration, Washington, DC.

A.13 INDICATOR: Dissolved Oxygen

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: Research

APPLICATION: The dissolved oxygen (DO) indicator is designed to provide data on estuarine ecosystem processes and on the habitability of estuarine waters for marine life, including economically important resources. Because these data needs are different, this fact sheet addresses DO as an exposure indicator of anoxic condition as it affects estuarine biota, whereas fact sheet A.1 addresses DO as an indicator of estuarine ecosystem processes. DO is a prime physical exposure indicator of water quality because (1) it is an essential requirement for all aerobic marine biota, (2) anaerobic conditions produce H_2S and NH_3 (highly toxic compounds), and (3) insufficient DO concentrations may increase the stress from other contaminants to marine organisms. Although causes of changes in DO concentration are complex, the ability to make meaningful measurements is readily available. As an exposure indicator that potentially impacts the benthic and fish response indicators, information on the temporal variability of DO is necessary. This research indicator is proposed so that the optimum deployment period for characterizing DO exposure may be established. These data would also be used to assess the representativeness of the DO measurements that indicate the result of ecosystem processes.

INDEX PERIOD: DO would be measured continuously over a 60-75-day period between June and September at up to 30 locations; this is the sampling window when hypoxia is most likely to occur. In addition, single point measurements would be completed at each station of an estuarine sampling unit during the time of mooring deployment and retrievals, as well as at the weekly meter servicing.

MEASUREMENTS: The method of choice is a system that employs a polarographic oxygen probe utilizing a plastic membrane on the sensor and is equipped with a data logger (Gnaiger 1983). These systems can be deployed in situ for periods of several days to one week. They will be serviced at approximately one-week intervals. Calibration is completed by Winkler titration with air calibration checks as a backup method. The advantage of the multiday in situ measurement is that it provides a more time-integrated exposure assessment than discrete samples. The capital costs for the deployed Hydrolab DO units are about $5600 each. The meters can be retrieved, serviced, calibrated, and redeployed by four mid-level field technicians in 1 h. During the index period, the meters will be serviced in this manner seven times.

It is difficult to assess all aspects of uncertainty (e.g., all relevant sensors [pressure transducer, conductivity cell, and thermistor] must provide usable data). A field calibration of accuracy, precision, and reliability is in order regardless of the in situ system deployed. The computed resolution of the Hydrolab system is in the range of 0.01 ppm, and accuracy is stated by the manufacturer to be ±0.2 ppm. DO saturation estimates include uncertainties in the thermistor and conductivity sensors.

VARIABILITY: The expected temporal variability among DO records during the index period would yield coefficients of variation >100%. The expected spatial variability of DO records within an estuarine sampling unit would produce a range that deviates >100% from the mean value.

PRIMARY PROBLEMS: Instrument error (e.g., drift) can be a problem for continuous in situ measurements, but methods exist for reasonable quality checks on the measurement system. The long deployment period would also make these units prone to vandalism and theft.

REFERENCE:

Gnaiger, E. 1983. In situ measurement of oxygen profiles in lakes: Microstratifications, oscillations, and the limits of comparison with chemical methods. Pages 245-264. In: E. Gnaiger and H. Forstner, eds. Polarographic Oxygen Sensors, Springer-Verlag, New York.

APPENDIX B: INDICATOR FACT SHEETS FOR INLAND SURFACE WATERS

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B.1 INDICATOR: Lake Trophic Status

CATEGORY: Response/ Ecosystem Process Rates

STATUS: High-Priority Research

APPLICATION: Excessive enrichment of lakes with nutrients has been a significant problem for some time. It is the most often cited problem that occurs in the Nation's lakes (U.S. EPA 1987). Early concerns centered around the release of organic material from point sources. The microbial degradation of these compounds resulted in decreased oxygen concentrations in receiving waters. Interest then shifted toward the role of point and nonpoint sources of inorganic nutrients, particularly P and N (Bachmann 1980; Dillon and Rigler 1974; Heiskary et al. 1987; Jones and Bachmann 1976; Larsen et al. 1988; Omernik et al. 1988; Smith 1982). The endpoints that are most often of public concern are (1) abundance of bloom-forming algae, which may lead to taste, odor, and toxicity problems, (2) formation of surface algal scums, (3) reduction of water clarity, which reduces aesthetic value, and (4) excessive growth of macrophytes, which reduces swimmable and boatable area. Several indices of lake condition based on trophic state have been developed (Brezonik 1984; Canfield and Jones 1984; Carlson 1977; Porcella et al. 1980; Shapiro 1979; Uttormark and Wall 1975; Walker 1984; Walmsley 1984). These trophic state indices (TSIs) generally utilize some combination of measures of chlorophyll-a (indication of phytoplankton biomass), total P or total N, and Secchi disk transparency (measure of water transparency).

INDEX PERIOD: The appropriate sampling window for lake trophic status is mid to late growing season (generally July-August), when transparency is lowest, chlorophyll concentration highest, and recreational use most intense.

MEASUREMENTS: The measurements needed for constructing TSIs vary. In general, TSIs require measurement of chlorophyll a (phycocyanin, a blue-green algal pigment can also be measured on the same sample to assess nuisance algal abundance), total P and total N (see indicator B.9, Routine Water Chemistry), and Secchi disk transparency or extinction coefficient (as measures of water clarity). It would take a technician <0.5 h to conduct the above measurements. The expected measurement error is 10%.

VARIABILITY: The expected spatial variability of trophic status measures within a lake sample unit ranges <10% from the mean value; however, the temporal variability within the index period is likely have coefficient of variation of 20-40% (Knowlton et al. 1984; Marshall and Peters 1989; Smeltzer et al. 1989).

PRIMARY PROBLEMS: Measurement of a TSI is relatively straightforward; however, interpretation of the results requires some care. As with other indicators, the expectation of the index value or attainable quality is expected to vary with region and lake type. Trophic condition spans a continuum from low-nutrient, low-biomass oligotrophic waters to high-nutrient, high-biomass eutrophic waters; all of these states can be considered natural. However, enrichment beyond what is regionally expected can become a problem. Dystrophic lakes, lakes containing large amounts of humic substances, do not fit well into most of the trophic state indices. Lakes impacted by excessive macrophyte growth are also not addressed well by this trophic index concept. The major problem or limitation of lake trophic indices as response indicators is that they provide only an index of condition relative to this specific problem and are relatively insensitive to the wider range of potential problems that can occur. Recently, attempts are being made to develop indices of lake condition which address a wider array of condition issues (Davic and DeShon 1989).

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B.2 INDICATOR: Fish Index of Biotic Integrity

CATEGORY: Response/ Community Structure

STATUS: High-Priority Research

APPLICATION: The Index of Biotic Integrity (IBI) is used to measure health and complexity of a fish assemblage relative to those of assemblages at a series of minimally impacted sites of similar size from the same ecological region (Fausch et al. 1984; Karr et al. 1986). Values range from 12 (very poor) to 60 (excellent). It is used to measure the sensitivity of fish to a wide range of anthropogenic stressors (eutrophication, acidification, contaminants, physical habitat degradation, flow modification, introduced species, thermal pollution, overharvest). The IBI metrics are used to assess taxonomic richness, habitat and trophic guilds, sensitive (canary) species, generally tolerant species, individual condition, and abundance. When the fish assemblage is assessed, results are less variable and more rapidly obtained than those determined from measurements of ecosystem and population processes. The 12 metrics that make up the IBI differ in their sensitivities to stressors. For example, eutrophication results in shifts from insectivory to omnivory, contaminants reduce species richness, and thermal pollution increases the abundance of tolerant species.

The IBI was recommended in the EPA's bioassessment protocol for inland waters (Plafkin et al. 1989) and by participants in an EPA environmental indicators workshop (U.S. EPA 1989). The IBI is applicable to streams and rivers throughout the Midwest and in Oregon, California, Colorado, Appalachia, and New England (Miller et al. 1988). It has been used in Canada (Steedman 1988) and France (Oberdorff and Hughes 1989); its acceptance is further supported by applications documented in more than 30 journal publications. Modifications for use in the Southwest and Southeast and in lakes have not been completed.

INDEX PERIOD: Collections should occur in summer, during periods of relatively stable flows and temperatures. Storm flows and major migratory events should be avoided. The actual calendar dates would vary with latitude and altitude.

MEASUREMENTS: Field measurements include number and age class of individuals for each fish species and the incidence of disease or anomalies. All measurements are made by experienced taxonomists or fish biologists. Sampling gear (electrofishers, seines, toxicants, gill nets, traps) varies regionally and with water body size and type. Sampling is most effective in nearshore areas, in a variety of habitats (pools, riffles, bars, runs), and in areas of concealment. Collection effort varies from 1 to 5 workhours per person and requires a minimum of two persons (a competent taxonomist and one or more technicians). A small number of laboratory identifications may be necessary for some species and for voucher (quality assurance) specimens; 0.5-1.0 h per resource sampling unit is needed to calculate the index. IBI metrics include (1) the number of native fish species, darter/benthic species, sunfish/water column species, sucker/long-lived species, intolerant species, and individuals and (2) the percent of top carnivore individuals, tolerant individuals, omnivorous individuals, insectivorous individuals, exotic/hybrid individuals, and diseased individuals.

Field data for each metric are scored as 5, 3, or 1, the score depending on whether they are similar to, deviate slightly from, or deviate greatly from reference sites. Hughes and Gammon (1987) used ± for marginal values, and Ohio EPA (1988) recommends scoring proportional metrics as 1 when the catch is much lower than expected. Some redundancy is built into the IBI. This reduces measurement error (estimated at 5%), but may disguise important changes, unless the staff examine each metric for those changes.

VARIABILITY: Previous research (Karr et al. 1986; Hughes and Gammon 1987; Ohio EPA 1988) indicates a difference of 4 IBI points, or 10%, is considered significant change at a site. As long as the habitat is stable, there should be very little difference in spatial or temporal replicates. In a study of 105 regional reference sites in Ohio (sampled two to three times over two summers), 95% of the IBI values were ±5.6 from the true overall means of the sites; 75% of the IBI values were ±3.3 from the site means. Standard errors were <4 (Ohio EPA 1988). Highly perturbed habitats demonstrate greater variability than minimally impacted systems (Ohio EPA 1988; Karr et al. 1987), and the use of fewer metrics also increases variance (Miller et al. 1988).

PRIMARY PROBLEMS: For nationwide implementation, the IBI must be evaluated for use in the Southwest, the Southeast, and in lakes and reservoirs. Temporal and spatial variability should be further assessed through examination of several statewide data sets. Relationships between individual metrics and particular stressors need greater clarification before the index is used as a diagnostic tool. A series of reference water bodies (Hughes et al. 1986) in each ecoregion of the United States must be sampled to determine what IBI values are nominal (acceptable, attainable, unimpaired, indicative of health). The IBI has been used rarely in cold water systems (Miller et al. 1988; Steedman 1988) and is inappropriate in waters containing few fish species.

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B.3 INDICATOR: Macroinvertebrate Assemblage

CATEGORY: Response/ Community Structure

STATUS: High-Priority Research

APPLICATION: The macroinvertebrate community index can provide a measure of health and complexity of variously impacted sites with similar habitat in the same ecological region (Ohio EPA 1988; Plafkin et al. 1989). The various indices available incorporate several structural and functional metrics that differ in their sensitivities to physical and chemical stressors. Taken together these metrics can be sensitive to eutrophication, acidification, contaminants, physical habitat degradation, introduced species, and thermal pollution. Introduced predators typically impact the larger taxa, acidification reduces Ephemeroptera-Plecoptera-Trichoptera (EPT) taxa, and eutrophication increases the abundance of tolerant taxa.

Although macroinvertebrate assemblages are widely sampled and analyzed by state water pollution biologists, there is no widely accepted multimetric index for these assemblages like the Index of Biotic Integrity for fish at this time; however, several have been proposed recently, and these are being evaluated. Participants at an EPA indicators workshop highly recommended the benthic community as an ecological indicator (U.S. EPA 1989).

INDEX PERIOD: Nationwide, the most appropriate collection period is summer. Mid to late summer is preferred in temperate zones; however, in the southern states, winter can be an excellent time. Sampling is most effective when food supplies, flows, and temperatures are relatively stable and when later instars of insects are most abundant. Because of the high development rates of many macroinvertebrates, it is crucial that collections within an ecoregion occur over a relatively short period and during stable periods.

MEASUREMENTS: The raw data recorded are the number of individuals of each species. An experienced taxonomist is needed for making accurate identifications. Standard taxonomic references would be used to identify taxa to the lowest practical level. Although keys are available that allow identification of most macroinvertebrates to the generic level (e.g., Edmunds et al. 1976; Merrit and Cummins 1984; Pennak 1989; Wiggins 1977), species-level keys may need to be identified regionally for some groups.

Different semiquantitative sampling devices are effective for different habitats. Kick netting with a standard level of effort is appropriate in gravel riffles and runs, whereas aquatic sweep nets can be used for macrophytes and snags. Sampling of the more stable substrates in a variety of erosional habitats (e.g., riffles, bars) is recommended. Collection effort is estimated at 1-2 h for two persons; laboratory sorting and identifications are expected to require 3-5 h per sample. At $25/h, the laboratory work could cost $75-$125, or an average of $100 per sample (Plafkin et al. 1989). Candidate metrics to be evaluated include counts of total taxa, mayfly taxa, caddis fly taxa, true fly taxa, and EPT taxa; percentages of tolerant individuals, intolerant individuals, true fly/noninsect individuals; percent contribution of dominant taxon individuals, scraper individuals, shredder individuals, collector individuals; modified Hilsenhoff biotic index (Hilsenoff 1982); and chironomid abundances.

VARIABILITY: It is essential to limit natural variability by careful choice of index period, sampling method, and habitat; by using a consistent sampling effort; and by analyzing multiple structural and functional characteristics of the assemblage. Despite such precautions, high variability is likely because of the high spatial variability of the benthos, high development rates of the animals, and their varied microhabitat requirements. In a study conducted in one run of a high-quality creek, Ohio EPA (1988) found its invertebrate community index varied by only 4 points (6%) between the 25th and 75th percentiles; however, sampling stations were standardized for physical habitat. Fiske (1988), also standardizing for substrate, reports that only metric values 10-50% different from the controls are considered significant. Combining metrics would reduce this measurement variability, but sampling natural habitats rather than standard substrate would increase it.

Natural spatial variability within the resource sampling unit or temporal variability during the index period are expected to have a range that deviates 10-30% from the mean values of different metrics (Bode and Novak 1988; Courtemanch and Davies 1988).

PRIMARY PROBLEMS: Before nationwide implementation, the series of candidate metrics must be rigorously evaluated (singly and in combination) through use of available data sets from across the country. Both spatial variability and temporal variability need greater evaluation. Metric and index sensitivities to various stressors must be examined, and a series of ecoregional reference sites (Hughes et al. 1986) should be selected and sampled.

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B.4 INDICATOR: Relative Abundance of Semiaquatic Vertebrates

CATEGORY: Response/ Community Structure

STATUS: High-Priority Research

APPLICATION: The relative abundance of semiaquatic vertebrates (amphibians, reptiles, birds, mammals) is an important measure of environmental health to the public. Semiaquatic vertebrates are among the first organisms to suffer from physical habitat modifications and overharvest. Birds appear to be the taxonomic group which can be sampled most efficiently. They are easily identified during the breeding season by observation or song. Amphibians and mammals, on the other hand, are much more difficult to sample, requiring a labor-intensive trapping or search method. Amphibians are still under consideration, however, because of their sensitivity to environmental disturbance, as well as the concern that their populations are declining.

INDEX PERIOD: The optimum sampling period for birds is during the June breeding season, with observations earlier or later in the month, depending upon latitude. Because birdsong is an important means of identification, sampling any later than mid-July would be ineffective. Field visits later in the season would also tend to record transient birds in addition to residents.

MEASUREMENTS: A random, single visit sampling frame already exists in the U.S. Fish and Wildlife Service Breeding Bird Survey (BBS). Regional trends in individual bird species have been traced over 25 years. Although there is no bird community index as advanced as Karr's Index of Biotic Integrity for fish (see indicator B.2), much work has been done with bird communities and guilds (Short and Burnham 1982; Verner 1984; Brooks 1989). Brooks' response guilds use metrics based on a species' wetland dependency, habitat specificity, and trophic level. Elements of both the BBS methodology and Brooks' response guilds could be adapted to the EMAP framework. Mammal presence, especially beaver, otter, muskrat, and nutria, can be assessed from sign (burrows, lodges, slides, tracks, feeding remains, scat).

The average time to complete a 25-mile BBS auto transect is 4 h. The time to walk or canoe a transect along an inland waters sampling unit may require 2 to 4 h, depending upon the size of the sampling unit and length of transect. Accurate surveys require a field crew familiar with bird habits and song and mammal sign.

Sampling error depends upon the differing skills of field staff. For example, Faanes and Bystrak (1981) report a 20% sampling error for birds recorded in the BBS. As many as one third of the species detected by one observer may be missed by another. Second-year participants reported 3-11% more species than new participants. Birds may be misidentified by observers of any experience level (Robbins et al. 1986). Robbins et al. stress that this variability of detection does not detract from the validity of the BBS. The misidentifications and overlooked species balance out over the years. The survey is a random sample which provides a regional picture of bird population trends. Measurement error is reduced by having a well-trained field crew follow standardized field procedures.

VARIABILITY: The expected spatial variability of bird populations within resource sampling units results from their high mobility. Suitable habitat may not be used consistently from year to year, depending upon changes in recruitment and survival. Species also vary in their site tenacity in locating nesting sites.

The expected temporal variability of local breeding bird populations during the index period is due to climate fluctuations and conditions on the wintering grounds. Poor weather conditions and wind or water noise may also interfere with field observation.

PRIMARY PROBLEMS: Avian response guilds must be constructed for various regions of the country. Response guild metrics should be tested in both the aggregated and disaggregated state. The optimum index period differs from the late summer sampling window of other response indicators (fish, trophic state). The nominal-subnominal boundary must be defined by selection and sampling of regional reference sites of each ecosystem type.

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B.5 INDICATOR: Diatom Assemblages in Lake Sediments

CATEGORY: Response/ Community Structure (Retrospective)

STATUS: High-Priority Research

APPLICATION: Diatom assemblages are important components of aquatic ecosystems and are proven indicators for evaluating present surface water quality and for making comparison with historical or reference conditions. A number of taxa correlate strongly (positively and negatively) with various water quality variables and can be used to reconstruct specific lakewater characteristics (Lowe 1974). Species vary in their response to eutrophication (Smol et al. 1983; Agbeti and Dickman 1989), acidification (Charles et al. 1989), and recovery (Dixit et al. 1990), metal contamination (Dixit et al. 1988, 1990; Kingston and Birks 1990), salinification (Fritz and Battarbee 1986), thermal alterations (Smol 1988), and land use changes (Tuchman et al. 1984; Bradbury 1986). The use of diatoms in environmental assessment is not an experimental technique; it has already been effectively used in answering a diverse set of environmental questions in many regions of North America. The application of this indicator is appropriate nationwide.

INDEX PERIOD: Because surface sediments integrate diatoms temporally the samples can be collected at any given time. A surface sediment assemblage can represent one to several years of accumulation, depending on the resolution attained in sectioning the cores.

MEASUREMENTS: Sediment cores should be generally taken from the deep basin for surface sample or stratigraphic analysis. Sediment cores offer a unique historical perspective of the nominal or reference condition of lakes. Sophisticated coring and sectioning techniques are available (e.g., Glew 1988) to provide fine temporal resolution and biological detail of changes occurring between years (Dixit et al. 1989, 1990).

Diatom identification and enumeration are made by following standardized taxonomic procedures such as those developed during the Paleoecological Investigation of Recent Lake Acidification (PIRLA) project (Camburn et al. 1984-1986). Presence and absence of indicator species, early warning indicators, species richness and diversity, relative composition of species, and relative proportions of indicator assemblages are determined from the data set. Multivariate assessment of indicator response to individual stressors is made by using Canonical Correspondence Analysis (ter Braak 1986). A variable score can be easily developed, compared with scores for reference sites, and synthesized into an index that represents overall ecosystem condition or health. The weighted averaging regression and calibration technique (Birks et al. 1990) is used to develop predictive or inference models for multiple environmental variables. Sophisticated error estimation techniques are also available for diatom inferences (Birks et al. 1990). For a number of environmental variables, the error associated with diatom models is known. For example, in the PIRLA II research, estimations of pH (mean standard deviation [SD; ±0.28]), acid neutralizing capacity (±12 µequiv/L), monomeric aluminum (±1.3 µmol/L), and dissolved organic carbon (±55 µmol/L) are made with high accuracy (Sullivan et al. 1990). This means that the diatom assemblage can be used to check long-term levels of exposure variables that will otherwise be measured only once in 4 years.

A sediment core can be easily taken and sectioned by two technicians in 2-3 h. Sample preparation, taxonomic identification, and counting (500 valves or frustules) requires one technician or frustules and eight expert hours per sample. At $8/h for a laboratory technician and $20/h for a taxonomist, the cost per sample analysis is approximately $170. Although the number of samples required for analysis from each core will depend on the type of information sought, it would be necessary to analyze at least three samples per core to obtain historic information. The analysis of a single surface sediment sample from a lake sampling unit would be sufficient for subsequent sampling runs.

Core collection and sectioning (SD for pH = <0.16; n = 3) and the sample preparation (SD for pH = 0.04; n = 8) for microscopic study is relatively straightforward, and variation from this source is minimal and can be quantified (Charles et al. 1990).

VARIABILITY: Because surface sediments integrate over time, the temporal variability of diatom assemblages throughout the year is inconsequential. The expected spatial variability of an assemblage within a lake sampling unit is low. The standard deviation of pH predictions based on assemblages was only 0.21 ($n=16$). A deep water core provides a reliable environmental assessment of an entire lake (Charles et al. 1990). The protocol produced in the PIRLA project provides a good model for sampling design (Charles and Whitehead 1986).

PRIMARY PROBLEMS: Although large ecological data sets are available for lake environments in the eastern United States and the northern Great Lakes states, such sets for other ecoregions of the United States would be necessary to further develop taxonomic capability for relatively unstudied regions of the United States, including preparation of photographic plates and reference slides. Taxonomic research is important because the biggest source of inaccuracy in diatom analysis comes from inconsistent or inaccurate identifications. The approach used to promote correct and consistent taxonomy in PIRLA research (Camburn et al. 1984-1986; Charles and Whitehead 1986) can be easily adapted for a nationwide monitoring program.

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B.6 INDICATOR: Top Carnivore Index: Fish

CATEGORY: Response

STATUS: High-Priority Research

APPLICATION: This indicator relates directly to the "fishable" endpoint because the top carnivores in most inland aquatic ecosystems are sport fish, and they provide an important assessment of species commonly valued by the public. The relative abundance of juveniles, adults, and large adults indicates the adequacy of the site for rearing and reproduction and the potential impact of bioaccumulation. These vertebrates are sensitive to overharvest, acid deposition, contaminants, and physical habitat/flow modification. Partial diagnosis is possible through association with known or suspected stressors. The application of this indicator is appropriate nationwide.

INDEX PERIOD: Collections should occur in summer, during periods of relatively stable flows and temperatures. Storm flows and major migratory events should be avoided. The actual calendar dates would vary with latitude and altitude.

MEASUREMENTS: This is essentially the top carnivore metric of the Index of Biotic Integrity (IBI) indicator (B.2) and only requires indicating the size/age class of those fishes. No additional time, equipment, staff, or analyses are needed. In trout streams that support only one to three fish species, this may be the only fish assemblage indicator measured. For lakes, Casselman et al. (1985) estimated measurement error as having coefficients of variation (CV) from 44 to 84%, the CV depending on species and gear type.

VARIABILITY: The variability of this single metric is greater than that of the IBI values because top carnivores tend toward rareness naturally and because the multimetric IBI offers no redundancy. For lakes, the estimated CVs for natural variability range from 24 to 27% (Casselman et al. 1985). Most of this variability is a result of temporal variability within the index period, rather than spatial variability within the lake sampling unit.

PRIMARY PROBLEMS: In fish assemblages composed of only one or two species (trout streams), population estimates from two to three catch or removal sampling passes are needed for accurate evaluation. A duplicate catch or removal pass is a standard fishery technique for streams, but lake estimates from gill netting and electrofishing are likely to be biased toward larger and littoral individuals, respectively (Hocutt and Stauffer 1980).

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B.7 INDICATOR: External Pathology: Fish

CATEGORY: Response/ Pathology

STATUS: High-Priority Research

APPLICATION: Stressors in general produce functional change in particular cells, tissues, and organs. If the timing, duration, or intensity of these stressors is sufficient, structural changes occur. Eventually, changes in fish populations and the assemblage occur. Typically, pathology increases as Index of Biotic Integrity (IBI; see indicator B.2) scores decline and as the level of contaminants and pathogens rises. In addition, the public is sensitive to this concern because of the fear of cancer and birth defects. Eutrophication affects gill and fin structure, and the skin and skeleton are affected by contaminants. This indicator is appropriate worldwide and is also an IBI metric.

INDEX PERIOD: The optimal sampling window is summer or when species are most stressed.

MEASUREMENTS: The eyes, fins, scales, operculum, and gills of all fish are analyzed in the field. A checklist is used by a trained technician; the time required for the examination is <0.5 h, depending on the number of fish examined. The expected measurement error is <5%.

VARIABILITY: According to previous use in the western and midwestern United States (Hughes and Gammon 1987; Ohio EPA 1988), the expected spatial variability of gross fish pathology within a resource sampling unit and its temporal variability during the index period each produce ranges that deviate <10% from their mean values, although individual metrics have 0-65% variability among observers (Goede 1988). Measures of external pathology have the lowest variability.

PRIMARY PROBLEMS: Regional reference sites are used to define normal or acceptable conditions; therefore, the reference sites must be selected and sampled before measurements are analyzed.

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B.8 INDICATOR: Water Column and Sediment Toxicity

CATEGORY: Exposure and Habitat/ Bioassays

STATUS: High-Priority Research

APPLICATION: Toxicity indicators are designed to estimate regional incidence of acute or chronic toxicity of water and sediment in streams, rivers, lakes, and reservoirs. Acute toxicity is used to determine if short-term exposure to ambient samples results in mortality. Chronic toxicity is a measure of longer term exposures that may result in reduced growth or reproduction of test species. Water column toxicity is a critical indicator of water quality and has been given considerable emphasis in the Water Quality Act of 1987 (Mount et al. 1984, 1986; Lazorchak and Love 1985; Burton et al. 1987a,b; Braidech et al. 1988; Lazorchak et al. 1989; Willingham et al. 1989). The Congress, the EPA, the States, and the public have placed a significant emphasis on achieving a nontoxic environment. Sediment toxicity is an important indicator of sediment quality. Both short- and long-term accumulations of toxics have been detected by this indicator (Nebeker et al. 1984; Burton et al. 1987a, b). When used with results of water column toxicity, sediment toxicity will give an estimate of total community exposure to toxic substances.

The results from acute and chronic invertebrate, fish, and plant toxicity tests determine if pollutants are present in toxic amounts in water bodies. The proportion of waters exposed to toxics as compared to other stressors can be estimated.

INDEX PERIOD: Acute and chronic effects from all sources can be measured during late summer or early autumn low-flow periods, when contaminant concentrations are likely to be at maxima.

MEASUREMENTS: Standard tests for water column toxicity, available from EPA, are being used in the National Pollution Discharge Elimination System (NPDES) permitting program to measure effluent toxicity (Peltier and Weber 1985; Weber et al. 1989). Also, standard tests available from the American Society for Testing and Materials (ASTM) and from EPA are being used to evaluate sediment quality in the Great Lakes and large to medium size rivers (U.S. EPA/Corps of Engineers 1977; Nebeker et al. 1984; Nelson et al. 1989). These tests are useful diagnostic tools to assess the success of nonpoint and point source strategies for controlling exposure to toxic substances.

Samples are collected from streams or lakes and shipped to the laboratory or brought to a staging area such as a mobile laboratory within 24 to 48 h of collection. At the fixed or mobile laboratory, ambient water samples are allocated such that fish and invertebrate acute and chronic tests, as well as a 4-day algal or duckweed growth test, can be performed. Whole sediments and water extracts from sediments can be used to test for chronic toxicity to fish, planktonic invertebrates, algae, and duckweed. An acute sediment toxicity test is performed on a burrowing macroinvertebrate. Testing both extracts and whole sediments provides the advantage of distinguishing toxics contained in the interstitial water from those attached to the sediments themselves.

Acute tests of fish and invertebrate planktonic and benthic species, performed with ambient water or sediment extract, measure lethal effects over a 2-day period (static renewed daily) that are significantly different from effects measured in a composite reference sediment and water obtained from a series of minimally impacted reference sites for each region. Performance controls (standard laboratory water and sediment) are used as a quality assurance check against reference site water and sediment in case such water is toxic to or incompatible with the test organism. The estimated cost of 1 h per day plus test organisms is $100 per sample.

Chronic tests of fish with ambient water and sediment extract are used to measure growth differences during a 7-day period (static renewed daily) in comparison to data for a standard laboratory water extract or reference site water or sediment extract. The estimated cost of 0.5 h per day plus test organisms is $125 per sample.

Chronic tests of invertebrate species, conducted with planktonic species and ambient water or sediment extract, measure a reduction in reproduction over a 7-day period (static renewed daily) in comparison to data for a standard water extract or reference site water or sediment extract. The estimated cost of 0.5 h per day and organisms is $125 per sample.

Chronic tests of invertebrate benthic species with whole sediment measure growth differences during a 7- to 10-day exposure period in comparison to a standard water and reference sediment. The estimated cost of 1 h per day and test organisms is $200-$275 per sample.

Algal chronic tests, conducted with ambient water or sediment extract, measure the difference in algal growth over a 4-day period in comparison to a standard water extract or reference site water or sediment extract. Chronic tests of rooted aquatic plant (duckweed) measure the differences in chlorophyll a, biomass, and number of fronds over a 4-day period (static renewed daily) in comparison to a standard water extract or reference site water or sediment extract. The estimated cost of 0.5 h per day and tests organisms is $150 per sample.

Sampling time per site should be <1 h at a cost of $25. This could be significantly lower when integrated with time used for other chemical or biological sampling. The coefficient of variation for these methods ranges between 30 and 35%.

VARIABILITY: It is expected that spatial variation in contaminant concentrations within a resource sampling unit and temporal variation during the index period will far exceed the individual indicator test variation (see indicator B.10, Chemical Contaminants in Water Column).

PRIMARY PROBLEMS: No major problems are anticipated. Some modification of existing ASTM and EPA methods for sediment testing may be necessary to fit EMAP needs. Only logistic and monetary constraints can be expected.

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B.9 INDICATOR: Chemical Contaminants in Fish

CATEGORY: Exposure and Habitat/ Tissue Concentrations

STATUS: High-Priority Research

APPLICATION: Thousands of chemicals that are produced or mobilized by humans are released into the aquatic environment. Most of these compounds, however, are not accumulated by biota. Only compounds that are relatively stable and have certain physical or chemical properties bioaccumulate to high concentrations in aquatic organisms. Examples of chemicals known to bioaccumulate in organisms include polychlorinated biphenyls (PCBs), chlorinated pesticides, polycyclic aromatic hydrocarbons, and metals. Many of these occur in nearly nondetectable concentrations in water or sediments, yet when they accumulate in top consumers, they may cause reproductive, carcinogenic, or teratogenic problems. Therefore, measurement of selected chemicals in fish tissues is proposed to determine the extent of contamination in the nation's inland waters.

Examination of tissue concentrations for these compounds should allow for detection of contamination, even when concentrations in ambient waters are below detection limits, and a comparison between tissue concentrations and existing toxicological data should provide information regarding the potential risk to the exposed organisms. Examination of fish tissue concentrations can provide an early warning for exposure to animals higher in the food chain such as aquatic birds and mammals. Also, detection of contaminants in important commercial and sport species would provide information regarding risks to human health through consumption of contaminated organisms. Finally, because the method involves the measurement of specific chemicals, this indicator has high diagnostic value, allowing for inferences to be made regarding potential sources of contamination.

INDEX PERIOD: The selection of an index period for measuring fish tissue contamination would probably be based on ease of sampling more than any other factor. Low-flow periods in the summer months may prove to be the best time to collect fish for this purpose.

MEASUREMENTS: The U.S. Fish and Wildlife Service (FWS) routinely analyzes 114 organic chemicals and 23 metals in its national contaminant monitoring program (U.S. FWS 1989). Methods for analysis of the 66 analytes in the National Bioaccumulation Study (NBS) have been developed for whole-body samples by the EPA's Environmental Research Laboratory in Duluth. Existing analytical sample collection, preservation, and transport methods would be examined for their applicability to EMAP. Costs for conducting chemical analyses for the NBS have been estimated at $2000-$2500 per fish sample. In addition to these methods, methods developed in the U.S. National Oceanic and Atmospheric Administration (NOAA) Status and Trends Program for measuring tissue contamination in estuarine and marine organisms (see indicator A.13, Chemical Contaminants in Fish and Shellfish) may prove useful in the development of this indicator for EMAP (Tetra Tech 1986; U.S. NOAA 1985, 1988). For more sensitive analyses, EMAP investigators may choose to examine specific types of tissues, such as the liver, which is known to show higher contaminant levels than whole-body samples for a number of compounds. The liver is also often a target organ for many of these compounds.

Where numeric criteria do not exist, selection of values of concern for each compound could be based on U.S. Food and Drug Administration action levels or state "levels of concern." An alternative method would be to base this delineation on data collected at NBS background sites or EMAP reference sites.

One parameter that is important for interpreting this indicator is the lipid content of the fish. Some of the compounds known to bioaccumulate are highly lipophilic, and their concentrations in fish tissue would be directly related to the lipid content of the organism; therefore, data need to be expressed as nanogram or microgram per gram lipid weight, as well as nanogram or microgram per gram wet weight and dry weight.

Information may also be needed to normalize the data on the sex and reproductive state of the fish, both of which affect lipid content.

The error associated with measuring contaminant concentrations in tissues would depend on the contaminants chosen, the specific tissue preparation and analytical methods selected, and the interlaboratory variability that is encountered when more than one laboratory is used to analyze the samples. Data from the NBS would help identify some of these sources of error; however, all NBS data were analyzed at ERL-Duluth. FWS and NOAA data are available, and scientists from the former recommend a single laboratory to reduce interlaboratory variability (Kefner 1990). Acceptable precision and accuracy are 10-32% (Smith 1989).

One option that would significantly reduce monitoring costs is to analyze tissues from a subset of the EMAP sampling units and to coordinate sampling with other state and federal agencies that monitor tissue contamination. The danger with this approach is that the EMAP grid design may be violated or that the sampling density would be inadequate.

The Federal Water Pollution Control Act establishes a process for developing information about the quality of the nation's water resources and reporting this information to the EPA and the U.S. Congress; therefore, national data bases of contaminants in fish tissues already exist, but their inability to produce unbiased regional and national estimates with known confidence has reduced the value of this data. In the National Water Quality Inventory - 1988 report to Congress (U.S. EPA 1989), 46 states and U.S. territories reported on fishing bans or advisories due to contaminated fish tissues; 585 fishing advisories and 134 bans were identified for the 1986-1988 period. PCBs, mercury, dioxin, and DDT were the most commonly cited causes; industrial discharges and land disposal were the most common sources of contamination. The report did not attempt to correlate contaminant tissue levels in fish with adverse effects on the aquatic ecosystem or any component thereof (e.g., organism, population, community). Also, states tend to focus their efforts on those water bodies most likely to be impacted by anthropogenic activities. As a result, the representativeness of the data contained in this report to Congress is unknown, and therefore the information has little value in making regional-scale assessments of the overall extent of inland water contamination.

In addition to the activities of the states in monitoring tissue contamination, the EPA initiated the NBS in 1986. The study is a one-time screening activity designed to determine the extent to which water pollutants are bioaccumulating in fish and to identify correlations with sources of contamination. In the study, fish sampled from approximately 400 sites throughout the United States are being analyzed for 66 highly bioaccumulative pollutants, including dioxins, PCBs, and several pesticides. Fish have been sampled at (1) potential problem sites with significant industrial, urban, or agricultural activity; (2) relatively undisturbed background areas; (3) locations with important sport or commercial fisheries; and (4) a number of locations randomly selected for nationwide coverage. The NBS results have been evaluated (Tetra Tech, Inc. 1990).

VARIABILITY: An examination of data from the randomly selected sites in the NBS would provide some estimate of the spatial variability and temporal variability within a resource sampling unit and during the index period, respectively.

PRIMARY PROBLEMS: As stated above, only certain types of chemicals bioaccumulate in fish tissue; therefore, the selection of chemicals to measure would be an important consideration. For many classes of compounds that do not bioaccumulate (e.g., ammonia, chlorine), this indicator would provide no information regarding their ability to impact aquatic ecosystems. As more and more chemicals are manufactured and introduced into the aquatic environment and the determination must be made of which compounds to monitor in fish tissue, EMAP strategists might want to rely on models capable of predicting the bioaccumulative nature of each compound based on its physical or chemical properties. Random site selection would probably miss most "hot spots" associated with point source discharges, but may provide a good indication of the extent of diffuse, nonpoint source loadings.

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B.10 INDICATOR: Routine Water Chemistry

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: High-Priority Research

APPLICATION: This indicator is composed of water quality parameters that measure the potential exposure of aquatic biota to common chemical and physical stressors. Several different groupings of these variables would be used to identify different categories of stressors.

Eutrophication: Excessive enrichment of lakes and streams with nutrients has long been considered a major problem threatening surface waters throughout the world. Blooms of nuisance algae, reduced water clarity, and fish mortality resulting from low dissolved oxygen (DO) are results of cultural eutrophication that concern the public. The loading of N and P in excessive amounts from nonpoint sources such as agricultural runoff or point sources like wastewater treatment facilities has been repeatedly linked to increases in phytoplankton biomass (Bachmann 1980; Dillon and Rigler 1974; Heiskary et al. 1987; Jones and Bachmann 1976; Larsen et al. 1988; Omernik et al. 1988) and reduction in water clarity. Because control of phytoplankton biomass appears to vary with respect to N and P concentrations (Smith 1979), both total N and total P should be measured. Summer and winter fish kills resulting from depletion of DO as a result of high algal biomass have also caused concerns in a number of areas (Barica and Mathias 1979; Casselman and Harvey 1975).

Acidic Deposition: A second anthropogenic stress of concern in surface waters is acidification of lakes and streams and its detrimental impact on the biota, particularly fish. Low pH, acid-neutralizing capacity (ANC), dissolved inorganic carbon (DIC), and dissolved organic carbon (DOC) can suggest acid deposition. The impact of acidic inputs of anthropogenic origin on the pH and ANC of surface waters has been evaluated (National Academy of Sciences 1981; National Research Council of Canada 1981), and the current chemical status of lakes and some streams within the United States has recently been established (Linthurst et al. 1986; Landers et al. 1987; Kaufmann et al. 1988). EMAP would track condition of biological components which might be impacted by acidic deposition, whereas previous spatially extensive studies have tracked primarily chemistry. ANC, pH, and SO_4^{2-} would be used in this program as diagnostic indicators to identify when acidic deposition is the most probable cause for classifying a fraction of the resource population.

Contamination, Thermal Alteration: High levels of residual Cl, total suspended solids (TSS), and total dissolved solids (TDS) are often associated with nontoxic contaminants and/or salinization problems. Unusually high or low water temperatures may indicate thermal pollution.

INDEX PERIOD: In general, the appropriate index period would be when the biological sampling is conducted. The peak growing season is the most appropriate time to measure components which are specific to eutrophication. Generally, a late July to early September index period would be suitable. This period would be near the time of maximum algal biomass. The times of fall mixing for lakes and of spring base flow for streams are the index periods which were used in the EPA National Surface Water Survey (NSWS) to measure acidic deposition; however, water chemistry data from spring, summer, and autumn are available from NSWS - Phase I which can be used to assess the comparability of a late summer measurement period to previously used spring and autumn index periods.

MEASUREMENTS: Parameters that would be measured are N, P, Cl, NH_4, Mg, K, Na, Ca, Al, SO_4^{2-}, NO_3, Mn, Fe, DO, Secchi depth, pH, ANC, DOC, DIC, conductivity, TDS, TSS, and temperature. Standard field and laboratory methods would be used; laboratory costs are estimated to average $300-$500 per resource sampling unit. In lakes, a mid-epilimnetic water sample for total N and total P would be taken. A profile of DO saturation would be taken in lakes and streams. In streams, however, DO saturation must be taken at a consistent time in early morning to avoid confusion resulting from diel shifts in DO. Total N and total P samples would be taken at the same time. An extensive literature base was developed during the NSWS for the collection, handling, analysis for and quality assurance of the measures specific to acidic deposition studies. The NSWS procedures would be followed to ensure comparability with the previous studies of the NSWS. It should be possible to keep measurement error to <10%.

VARIABILITY: The expected spatial variability of these physical and chemical measures within a resource sampling unit should produce ranges that deviate <10% from the mean values; however, temporal variability for many of the measures during the index period is likely to produce ranges that deviate 20-30% from the mean values.

PRIMARY PROBLEMS: In order for these exposure indicators to help determine probable stressors, expected baseline values from regional reference sites are needed. Considerable logistic and quality assurance effort is needed to select contract laboratories. The use of the total N and total P data would be relatively straightforward; however, the most appropriate way to summarize the DO data for lakes would require some development. Traditional methods for calculating and presenting hypolimnetic oxygen deficits require relatively extensive information about the morphometry of the lake. Morphometry data would be available for few EMAP lakes, and therefore we would have to present DO data in a different fashion. This method could be developed over the next year, evaluated with existing data, and field tested early in the program. For the acidic deposition issue, a major problem would be determining if it is necessary to sample during the fall and spring as in NSWS; if data from late summer are comparable enough to the NSWS data, the index period could be changed. This can be evaluated somewhat for lakes with the summer data from the EPA Eastern Lake Survey - Phase II and the EPA Long-Term Monitoring Network.

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B.11 INDICATOR: Physical Habitat Quality

CATEGORY: Exposure and Habitat/ Habitat

STATUS: High-Priority Research

APPLICATION: This indicator estimates instream and lake deterioration of physical habitat quality, a commonly recognized stressor of aquatic ecosystems that is measurable nationwide. Assessing habitat quality is an integral component of assessing the ecological status of lakes and streams. The authors of the 1972 Water Pollution Control Act recognized this by establishing the restoration and maintenance of physical integrity of the nation's waters as an objective.

Physical habitat integrity is a critical aspect of the abiotic component of any ecosystem and needs to be evaluated quantitatively by EMAP. Establishing physical habitat quality is important in meeting the EMAP goal of evaluating the effectiveness of control strategies and EMAP's objective of attributing probable cause of subnominal ecological condition. When ecological status of a lake or stream is determined to be subnominal and habitat quality has been found to be adequate, such damage can be attributed to other factors such as water quality. This is especially important in a monitoring system such as EMAP, where chemistry and toxicity are sampled too infrequently to detect spills, intentional dumping, or other episodic events. Without assessing habitat quality, establishing probable cause of ecological condition would be difficult.

National nonpoint-source assessments demonstrate that habitat alteration is a major cause of poor ecological condition in streams, rivers, and lakes (Judy et al. 1984; ASIWPCA 1985; U.S. EPA 1987). Guidance for evaluating use attainment in EPA's National Water Quality Standards program includes habitat assessment (U.S. EPA 1983). More recent policy development and bioassessment guidance for streams emphasize habitat assessment (U.S. EPA 1988; Plafkin et al. 1989). A statistically designed field assessment of physical habitat quality is needed to determine quantitatively the status and extent of habitat alteration in the streams, rivers, lakes, and reservoirs of the United States. Both instream and surrounding topographical features affect the quality and quantity of physical habitat, which in turn affects the structure and composition of resident biological communities. Where habitat condition differs substantially from reference conditions, habitat alteration is suspected.

INDEX PERIOD: A habitat quality assessment (HQA) would be performed quantitatively during the same index period as the other surface water assessments.

MEASUREMENTS: Habitat quality evaluation is accomplished by characterizing selected physical parameters and by systematic habitat assessment. Key parameters are identified to provide a consistent assessment of habitat quality. The necessary information is collected during biological surveys and during landscape characterization.

Physical characterization parameters to be measured are general land use and physical stream, lake, or reservoir characteristics. Physical characterization starts with the riparian zone and proceeds inlake or instream to sediment/substrate descriptions. Such information would provide insight as to what organisms should be present or are expected to be present. Also, data on water odors, surface oil, and recent and current weather conditions would be collected.

The predominate use of land surrounding the resource sampling unit would be characterized by remote sensing because of its potential effect on water quality. Local erosion, existing or potential, would be recorded in the field because movement of soil into a stream or lake alters the physical habitat and reduces biological integrity. Point and nonpoint sources, such as landfills, feedlots, wetlands, septic systems, dams, impoundments, and mines would also be identified from remote sensing and field data. The physical habitat parameters included in an HQA would be weighted so that habitat quality can be rated as excellent, good, fair, or poor.

In streams, the primary parameters measured would be bottom substrate, instream cover, embeddedness, silt cover, and flow velocity. Secondary characteristics, such as channel alteration, bottom scouring and deposition, and pool/riffle and run/bend ratios, would also be evaluated. Finally, bank stability, bank vegetation, and streamside cover would be measured.

In lakes, the primary variables are surface area, maximum depth, lake level fluctuation, hydrologic residence time, proportion of littoral surface area, coefficient of variation in lake depth, macrophyte cover, and substrate. Secondary characteristics include shoreline development or complexity, shoreline vegetation, and proportion of artificial shoreline.

A total score would be obtained for each resource sampling unit and compared to a series of ecoregional reference sites. The comparison provides a comparability measure by classifying each unit as unimpaired, slightly impaired, moderately impaired, or severely impaired, depending on the degree that the physical habitat deviates from reference conditions. Field sheets with the above information would be and filled out and scored by field crews. On the assumption that the sheets could be completed in 2 h, the estimated data collection costs are $25-$50 per resource sampling unit, the cost depending on the expertise of the sampling crew.

VARIABILITY: The expected spatial variability of an HQA within a resource sample unit was not estimated; the variability of individual measurements, however, produces ranges that deviate 10-20% from their mean values (Platts et al. 1983). The expected temporal variability of an HQA during the index period would produce a range that deviates >10% of the mean value only if periods of intense floods or droughts occur during the period.

PRIMARY PROBLEMS: Habitat assessment of small and medium-size streams and rivers is expected to be straightforward and present few problems, if staff are thoroughly trained and tested. Research is needed to test similar assessment methods for large water bodies.

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B.12 INDICATOR: Water Column Bacteria

CATEGORY: Exposure and Habitat/ Pathogens

STATUS: Research

APPLICATION: This indicator can be used in environmental monitoring to determine the extent to which water bodies are contaminated by pathogenic microorganisms. Two types of pathogen contamination can exist: (1) pathogenic organisms introduced into surface waters and (2) indigenous organisms that grow to high densities because of increased nutrient loading.

Contamination of the first type has been routinely assessed in the past by using fecal coliforms; however, in 1986 the EPA recommended two new indicators of fecal contamination, *Escherichia coli* and enterococci, for assessing surface water quality. Their density in bathing beach water samples has been shown to be directly related to gastrointestinal illness in swimmers (U.S. EPA 1986). Thus, monitoring for either one of these measures can be used to determine the risk of illness associated with exposure to human pathogens. The data from monitoring *E. coli* or enterococci helps characterize the quality not only of waters used for recreation, but also of source waters for drinking. The sources of fecal contamination may be inadequately treated sewage (point sources) or runoff from pastures, feed lots, and urban areas (nonpoint sources). In the National Water Quality Inventory - 1988 report to Congress (U.S. EPA 1989), the states reported that of the 30% of impaired river and stream lengths, 19% were affected by fecal contamination. Also, of the 25% of impaired lake and reservoir areas, 12% were affected by fecal contamination.

The second type of potential pathogenic contamination (i.e., increased levels of indigenous bacteria resulting from high organic nutrient loading) is not currently included in routine monitoring programs, although it has been examined in some special studies. EMAP strategists may choose to include certain species of indigenous bacteria in the program's inland surface water monitoring, because the density of potentially pathogenic bacteria is a possible indicator of exposure of humans, fish, and other animals to infectious doses of these organisms. Densities of these potential pathogens can then be compared with incidences of fish disease and kills and with reported incidences of human infection. Organisms such as *Aeromonas hydrophila* and *A. salmonicida* may cause fish diseases and subsequent kills. Also, *A. hydrophila* can cause wound infections in humans and other animals, and it has been shown to be pathogenic to reptiles (Shotts et al. 1972). Finally, the density of *A. hydrophila* in natural waters correlates closely with a number of parameters used to assess trophic condition (Rippy and Cabelli 1979).

INDEX PERIOD: Fluctuations in bacterial populations are frequent and depend on season as well as pollutants. In general, population densities will be highest in late summer and early autumn.

MEASUREMENTS: Routine methods for identifying and enumerating bacteria in environmental samples have been developed by the U.S. EPA (1985). Grab samples are collected and stored on ice before processing by membrane filtration, followed by growth of viable bacteria on selective media. Confirmation of species is made by biochemical tests or biotechnology methods. The analytical cost per assay is approximately $30.

In a study of the EPA membrane filter method for enterococci that involved 11 laboratories, the standard deviation between means of duplicates from analysts in the same laboratory was 0.150 (count/100 mL) + 5.16 (dilution factor), where the dilution factor = 100 divided by the volume of original sample filtered (U.S. EPA 1985). A similar study for *E. coli* showed the standard deviation between means of duplicates from analysts in the same laboratory to be 0.233 (count/100 mL) + 0.82 (dilution factor), where again the dilution factor = 100 divided by the volume of original sample filtered. Analysis of reference samples produced coefficients of variation of 24% and 29%, respectively (U.S. EPA 1985).

VARIABILITY: Bacterial population densities fluctuate frequently during the index period. Populations would also exhibit high spatial variability within a resource sampling unit. This variability can be reduced somewhat by collecting samples at consistent depths or water temperatures. Two multiyear studies were evaluated to generate an estimate of natural variability. The average log standard deviation for enterococci and *E. coli* in these studies (conducted in summertime) was 0.4 (U.S. EPA 1986).

PRIMARY PROBLEMS: Some baseline monitoring is needed to determine the sampling frequency necessary to meet data quality objectives. Also, the appropriateness of the selected index period must be evaluated.

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B.13 INDICATOR: Heavy Metals and Man-Made Organics (Toxics)

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: Research

APPLICATION: Thousands of chemicals are released either directly or indirectly into the aquatic environment. One component of a comprehensive program for monitoring these ecosystems is an analysis of water and sediment samples for the presence of the most toxic, stable, or prevalent of these compounds: the heavy metals and man-made organics. Information on the concentration of these environmental contaminants can then be correlated with observed impacts on biological communities to improve the diagnostic capabilities of the program.

INDEX PERIOD: Sampling should take place during low flow, when contaminant concentrations are likely to be at their highest because of low volume. For lakes, this index period is not as critical, especially if water levels are maintained fairly constant throughout the year. Sediment contamination would probably be more stable than water-column contamination, although sedimentation following peak flow may introduce toxics in high concentrations to the sediment on a seasonal basis.

MEASUREMENTS: Standard analytical methods exist for the analysis of most chemicals currently perceived to be hazardous to aquatic ecosystems. These methods have been published by the U.S. EPA (1978, 1982, 1983, 1986, 1988a,b, 1989), the U.S. Geological Survey (1972), the American Society for Testing and Materials (1988), and published jointly in a manual by the American Public Health Association, the American Water Works Association, and the Water Pollution Control Federation (1989). A number of metals can be evaluated in a single sample by inductively coupled plasma (ICP) emission spectroscopy. Recent developments with ICP/mass spectrometry (MS) may improve the resolution of this type of analysis and should be evaluated. For organic contaminants, gas chromatography (GC)/MS allows for the identification and quantification of a wide range of volatile and semivolatile organic compounds. Research is currently under way to develop liquid chromatography/MS methods for the identification and quantification of a number of nonvolatile organic compounds.

Current protocols for sample collection, storage, transport, and preparation need to be evaluated for their applicability to EMAP. Sample handling would, to a great extent, depend on the analytes selected for monitoring and the constraints imposed by the analytical methods employed. The cost of the analyses would also depend on the methods and analytes selected, but some estimates are available. Routine GC/MS screens for the 165 priority pollutants currently average $350-$400 per sample, and ICP analysis averages $250-$300 per sample.

The error associated with measuring ambient concentrations of contaminants would depend on the contaminants chosen, the specific sample handling and analytical methods selected, and the interlaboratory variability that is encountered when more than one laboratory is used to analyze the samples. Based on the results of several interlaboratory studies conducted at EPA's EMSL-Cincinnati laboratory, single-laboratory precision for most of the analytical methods applicable to EMAP is approximately 90% (10% error), and multiple-laboratory precision is approximately 80% (20% error).

One approach that would significantly reduce the cost for assessing this indicator would be to archive water and sediment samples (or extracts of these samples) and perform the chemical analyses only if data from the response indicators or the bioassays suggest high levels of toxic exposure.

National data bases of water quality indicators already exist, but their inability to support unbiased estimates with known confidence has hindered the value of the data. The Federal Water Pollution Control Act establishes a process for developing information about the quality of the nation's water resources and reporting this information to the EPA and the U.S. Congress. In the National Water Quality Inventory - 1988 report to Congress (U.S. EPA 1989), the states reported elevated levels of toxics in one third of monitored river distance and about one seventh of monitored lake area. Also, sediment contamination by toxics was reported by 33 states. The states reported 533 incidents, primarily caused by heavy metals, polychlorinated biphenyls, and pesticides. In addition, more than 1000 pollution-caused fish kills were reported by 35 states, representing roughly 36 million fish killed. Among the leading causes cited by the states were oil and gas, pesticides, ammonia, and chlorine. Commonly cited sources include agriculture, spills, and municipal and industrial discharges. The report did not attempt to compare contaminant levels with adverse effects on the aquatic ecosystem or any component thereof (e.g., organism, population, community). Also, states tend to focus their efforts on those water bodies most likely to be impacted by anthropogenic activities. As a result, the representativeness of the data contained in the report to Congress is unknown, and therefore, the data has little value in making regional-scale assessments of the extent of inland water contamination.

VARIABILITY: Few data currently exist on nonsampling variability, such as that due to spatial patchiness or temporal variability associated with seasonal loadings. The expected spatial variability of contaminant measures within a resource sampling unit, based on hazardous waste investigations, would produce ranges that deviate >100% from their mean values. The expected temporal variability of contaminant measures during the index period, based on hazardous waste investigations, also would produce ranges that deviate >100% from their mean values.

PRIMARY PROBLEMS: Random site selection would probably miss a number of "hot spots" associated with point-source discharges, but may provide a good indication of the extent of diffuse, nonpoint-source loadings. Agricultural activities may affect the data if sampling occurs shortly after application of agricultural chemicals. Also, selection of sampling sites near point-source discharges may bias the data set.

A protocol must be developed for selection of chemicals to be monitored in this program that is based on toxicological data, information on loadings and chemical stability, and available data on fate and transport. For many chemicals, detection in the environment does not correlate strongly with biological effects because of limited bioavailability, rapid degradation, and a number of other factors. In a program such as EMAP, only those chemicals expected to have significant adverse biological effects should be monitored. Where numeric criteria do not exist, selection of levels of concern for each compound could be based on EPA numerical standards or state "levels of concern," but some evaluation of the concentration is needed to assess risk or potential problem, especially for naturally occurring elements.

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APPENDIX C: INDICATOR FACT SHEETS FOR WETLANDS

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C.1 INDICATOR: Organic Matter and Sediment Accretion

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: High-Priority Research

APPLICATION: One function of wetlands is as filters for suspended solids carried into wetlands from eroded uplands. As such, wetlands are depositional sites for sediments. The rate of sedimentation, along with sediment source and sediment distribution within a wetland, can indicate hydrologic history (Brinson 1988), as well as changes in the surrounding landscape that result from accelerated rates of drainage or erosion.

In some cases, public awareness of the consequences of altered accretion rates on water quality is very high (e.g., in Louisiana, where wetlands are being lost, and around certain eutrophic lakes, where natural flushing has been cut off and lake bottoms are silting in at a high rate). On the whole, however, public understanding of the importance of this indicator is low.

Combined with information on change in wetland area, hydroperiod, and nutrient concentrations of incoming waters, accretion rates can be used to indicate trends in trophic status. Thus, the rate of organic matter accretion may indicate the long-term sustainability of the supporting environment. Significant changes in this rate may be an early warning of stress.

INDEX PERIOD: Annual accretion of sediment is usually measured during base flow conditions or during the driest time of year, but in general it is not highly variable throughout the year.

MEASUREMENTS: Measurement techniques for accretion consist of placing surfaces in the system so that materials can settle in a "natural" manner (Frazier 1967, Kolb and Van Lopik 1958). Samples of accreted material are collected on an annual or semiannual basis, and the volume and composition (e.g., organic matter, clay, sand, silt) are determined. Labor costs would be about 1 person-day per site.

The rate of subsidence due to geologic activity must be determined in conjunction with sedimentation and accretion and can be measured against permanent monuments established for that purpose. Loss of elevation in soil surface is measured against the monument whose elevation is fixed. Establishment of the monument will require 2 person-days per site, but monitoring costs are negligible. The recommended interannual sampling frequency for accretion and sedimentation is every year.

VARIABILITY: Locations for measuring accretion must be carefully selected to account for the spatial variability in microtopographical differences within a wetland. The expected spatial variability of sedimentation rates within a resource sampling unit would produce a range that deviates as much as 100% from the mean value. The temporal variability of accretion during the index period would depend directly on the hydrologic system and frequency of flooding and in general would be greater in a tidal wetland than in a riverine wetland.

PRIMARY PROBLEMS: The role of wetlands as sediment depositories in the landscape has often been quantified, but seldom on a regional or comparative basis. The high spatial variation in rates of accretion and sedimentation is problematic.

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C.2 INDICATOR: Wetland Extent and Type Diversity

CATEGORY: Response/ Ecosystem Process Rates and Storage
Exposure and Habitat/ Landscape

STATUS: High-Priority Research

APPLICATION: Functional attributes of wetlands, including processes such as water recharge and water treatment, are most importantly related to the areal extent and landscape context of wetlands. Landscape indicators also function as exposure and habitat indicators because the spatial patterns of wetlands provide a quantitative measure of the available habitat for many waterfowl, wading birds, and other animals whose life histories are linked to wet areas. Wetland size, patchiness, and contiguity are also important habitat parameters for many wetland animals (see Appendix G-3). Remote sensing offers a powerful tool for monitoring the condition of wetland resources. Remotely sensed data provide information on response indicators such as spatial extent, size, and distribution of wetland community types throughout the United States. Depending upon the classification schemes used, remote sensing can detect most community-level changes and some species-level vegetation changes.

INDEX PERIOD: The most common period to sample forested wetlands is during the growing season. This holds for herbaceous wetlands as well, except when aerial photography is used to determine extent of inundation, in which case a "wet season" index period is warranted. Where changes in dominant species or types between evergreen and deciduous wetlands are of concern or where canopy otherwise precludes detection of surface water, winter photography is warranted.

MEASUREMENTS: The first step in mapping wetland systems is to develop classification systems whereby mapped units can be categorized. Once an appropriate classification scheme has been adopted, wetland types and boundaries within regions of interest are mapped. To achieve an accurate and repeatable map of wetland spatial extent, type diversity, and spatial pattern, the limits and types of wetlands indicated by aerial photography are interpreted on a clear overlay, from which a rectified and georeferenced map is made. Photographs from different years can be used to determine changes in areal extent and type diversity.

Periodic aerial photographic reconnaissance and mapping are necessary to detect changes in spatial extent. Optimally, biannual overflights may be necessary in some areas of the country, whereas in others, it may be necessary to acquire photography only every 5 or 10 years. Initial frequency could be based on human population growth rates within a region; higher frequency (1 to 2 years) is warranted in high-growth-rate districts and lower frequency (3 to 5 years) in slower growing areas.

To measure changes in type diversity and within-wetland heterogeneity, annual aerial photographic reconnaissance and mapping may be sufficient. Interpretation may lead to misidentification of wetland type, but usually, such events occur <1% of the time. Of greater concern is the variability in coverage of some wetland types that results from seasonal or yearly variation in hydrology. There are potential problems in determining differences in wetland size from year to year as a result of variation in spatial extent that can be attributed to natural variation or to seasonal variation in rainfall patterns. In forested wetlands, changes in dominant canopy species are not easily detected by remote sensing unless the wetland has been logged; thus, a high measurement frequency is not crucial. On the other hand, herbaceous wetlands and those with open water are more likely to exhibit changes in shorter periods of time and may require annual or biennial photography and mapping. Historical photographs can be used to compare past status in areal extent and pattern with status as revealed by EMAP.

VARIABILITY: The areas of many wetlands change significantly as the result of variation in seasonal rainfall, at times covering larger expanses with a typical wetland signature and at other times showing the signature of drought-stressed vegetation or bare ground. Additional corroborating information such as direct measurement of hydroperiods and rainfall is required; otherwise, short-term changes in spatial coverage in some wetlands may be difficult to ascertain. Extreme values could deviate as much as 100% from the mean value during the index period; however, because this variability can easily be accounted for with corroborating climatic information, it is not expected to pose serious limitations. Identification of new roads, structures, fill, beaver diversions, and similar features can also suggest relatively abrupt changes in the spatial extent of a resource sampling unit. Because the sampling unit will be censused via remote sensing, considerations of the spatial variability of this indicator within a resource sampling unit is unwarranted.

PRIMARY PROBLEMS: The determination of regional changes in acreage, type diversity, and spatial patterns using remotely sensed data is a relatively commonplace task. No problems are foreseen that would limit the use of this indicator in EMAP to determine the status of wetland resources.

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C.3 INDICATOR: Abundance, Diversity, and Species Composition of Vegetation

CATEGORY: Response/ Community Structure
Exposure and Habitat/ Habitat

STATUS: High-Priority Research

APPLICATION: Vegetation is probably the most common wetland component that is used to detect change in ecological condition. Vegetative characteristics such as major species, life form, and density can indicate ecological productivity, water chemistry, landscape aesthetics, and animal habitat suitability (Brooks and Hughes 1988). Sampling methods are well developed. The community plant diversity and related process functions (e.g., water quality improvement) are not the only aspects of wetland vegetation that are valued by the general public. The importance of habitat -- a major component of which is vegetation -- in maintaining populations of endangered animal species is also recognized, although not always widely appreciated by the public (Lefebvre 1988). Wetland plants, because they are immobile, are reliable indicators of certain types of stressors.

Changes in vegetation patterns and species composition are community-level response indicators that integrate the effects of a wide variety of potential stressors. As a result, impacts to vegetative species cannot be attributed to certain types of stressors without simultaneous data on other factors (such as hydroperiod) and direct measurements of nutrient levels and pollutants. The measurement of community patterns relates directly to habitat condition. Vegetation may be used to assess ecological status in two basic ways:

(1) **Sensitive species:** Indicator plants for specific water quality parameters can be identified by comparing plant communities in wetlands where such parameters are known. Changes in the ratio of exotic to native species can be interpreted as a community-level response to anthropogenic impacts.

(2) **Community structure:** Plant community structure in wetlands reflects many biotic and abiotic interactions. The effects of inundation, soil composition and chemistry, nutrient availability, salinity, previous anthropogenic activities, fire, etc., all contribute to changing community structure and species composition. Probably the single most important contributing variable is hydrology (see indicator C.9, "Hydroperiod").

INDEX PERIOD: Most frequently, wetland vegetation measurements are conducted in mid-growing season. The dormant season should be avoided because at that time (1) many species have not yet emerged from the topsoil, (2) the species composition and diversity are not at maximum potential, and (3) the vegetation is in juvenile form, seed heads are not yet formed, and it is extremely difficult to identify many of the plant species. Early and late growing seasons are not considered suitable periods because there is greater variation in vegetation during these growth phases.

MEASUREMENTS: Two general parameters of vegetation, species composition and abundance, should be measured to develop a quantitative assessment of ecological status. The exact methods will depend on the community type that is to be sampled. Methods for sampling wetland vegetation are described by Frederickson and Reid (1988) and Britton and Greeson (1988), and include sampling by quadrats or transects. By measuring these two parameters, the following metrics can be developed: areal cover, species richness, relative abundance, relative dominance, importance values, diversity, presence/absence of indicator species, and spatial patterning. Vegetation analysis is labor-intensive, both in the field and in the laboratory (identifying and cataloging species). The expected cost to characterize community structure is approximately 3 person-days per resource sampling unit for field work and 3 person-days for laboratory work in sorting and identifying species and cataloging data.

VARIABILITY: The expected spatial variability of vegetation measures within resource sampling units can be relatively high (with ranges that deviate >100% from the mean value), depending on the patchiness of the community. If the quadrat sampling method is employed, a sufficient number of replicates is required to adequately characterize within-community variability. If line strip transects are employed, within-community variability is less problematic (ranges that deviate <10% from the mean value). The expected temporal variability of vegetation measures during the index period is low (ranges that deviate <10% from the mean value).

PRIMARY PROBLEMS: The biggest problems associated with vegetation as an indicator are the labor-intensive sampling regime and the insensitivity of some species to some stressor types.

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C.4 INDICATOR: Leaf Area, Solar Transmittance, and Greenness

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: Research

APPLICATION: Measurements of canopy closure (sunlight transmittance) and photosynthetic potential (leaf area and greenness) are indicators of the vegetative response to stressors that cause decreases in primary production or increases in respiration (see also indicators D.1, "Tree Growth Efficiency," and E.1, "Vegetation Biomass"). Long-term stress usually results in changes in community composition. In herbaceous wetlands, changes in community structure occur rapidly in response to stress, whereas in forested wetlands, changes in community structure take much longer to appear. The use of leaf area, sunlight transmittance, and greenness in these long-turnover-time systems may make the detection of stress easier. Ericaceous wetlands, in particular, will reflect changes in light absorption caused by stress.

Death of large numbers of plants in any one area will generate concern among some members of the public. Autumnal leaf drop in cypress forests brings telephone calls to county foresters and extension offices from alarmed citizens who believe the trees are dying. The concepts of leaf area and greenness in themselves, however, seem unlikely to have much meaning to the public.

An increased drop rate of green and yellow leaves can indicate the onset of stress. Declines in greenness may indicate stress; temporary surges in greenness may indicate nutrient enrichment during which the wetland is being invaded by upland species. Greenness can be used as an index of leaf area in forested wetlands and of areal cover in herbaceous wetlands.

INDEX PERIOD: Most frequently, wetland vegetation measurements are conducted in mid-growing season. Early and late growing seasons are not considered suitable periods because there is greater variation in vegetation during these growth phases.

MEASUREMENTS: Both aerial reconnaissance and field-derived data can be used to measure greenness. Greenness can be measured via remote sensing of reflectance in the visible bands and, for some applications, in the infrared bands. Canopy reflectance values measured with a hand-held Lycor reflectometer show differences that indicate definite signatures for differing community types (Odum et al. 1989). Further work may yield a quick method of determining condition by comparing reflectance of stressed and unstressed wetlands.

Greenness and its relationship to ecological stress, although used widely in agricultural applications, have not been extensively used in ecological monitoring. No greenness value is absolute; greenness as an indicator of stress or condition must always be evaluated in reference to greenness measured in a reference wetland.

Standard techniques for determination of leaf area index are relatively time-consuming, requiring the harvest and measurement of a known area of leaf biomass (requiring 2 to 3 person-days per resource sampling unit). Sunlight transmittance is measured by using a hand-held solarimeter at ground or water surface. Numerous replicate measurements are necessary within each wetland community. Simple measures require <1 person-hour per resource sampling unit.

The sampling frequency is determined by the desired level of temporal resolution in change. Synoptic one-time measurements should be sufficient to establish status of wetland condition. An annual or biennial sampling frequency is sufficient to determine overall trends in wetland condition; however, where more detail is desired to show effects of special events, monthly measurements on subsamples of the sample population would be necessary.

VARIABILITY: The expected spatial variability of these canopy measurements within a resource sampling unit would produce ranges that deviate >10% from the mean values. The expected temporal variability of canopy measurements during the index period was not estimated.

PRIMARY PROBLEMS: The greatest impediment to implementation is the lack of widespread use of the measures as indicators of ecological stress.

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C.5 INDICATOR: Macroinvertebrate Abundance, Biomass, and Species Composition

CATEGORY: Response/ Community Structure

STATUS: Research

APPLICATION: Aquatic insects (such as dragonflies and midges) are found in all wetland types, bioaccumulate to some extent, and are responsive to all four major wetland stresses (altered hydroperiod, excess sediment, changes in nutrient cycling, and contaminants). Benthic/epiphytic macrocrustaceans (such as amphipods, crayfish, oligochaetes, and isopods) have similar advantages as response indicators, but they are not as easily dispersed as aquatic insects and thus may be better indicators of conditions at specific sites. Mollusks, in addition to their immobility, are highly bioaccumulative; their deformities may indicate contamination.

Macroinvertebrates have been posited for a number of years as one of the most important indicators of ecological condition in aquatic environments. Several different measures have been used and/or proposed as effective means of determining wetland condition. They include measures of (1) sensitive species, (2) populations, and (3) community structure.

INDEX PERIOD: An optimal sampling window is mid-growing season. Sampling should not be done during or immediately after extreme events (e.g., drought, first flood, leafing, leaf-drop).

MEASUREMENTS: Sampling techniques (e.g., mesh size, gear type) must be the same in order to compare index values (Averett 1981). Methods of sampling invertebrates are discussed by Weber (1973), Merritt and Cummins (1984), and Frederickson and Reid (1988). In general, the methodology requires the collection of organisms living within a standard sized area or volumetric unit and the use of sweep nets or specially designed enclosing equipment. In some cases artificial substrate (e.g., plastic plants) having a known surface area can be placed in a wetland and allowed to be colonized; colonizing organisms are subsequently counted.

There is significant expenditure of time in the preparation, identification, and analysis of invertebrate samples in the laboratory. Collection, processing, and identification may take up to 40 person-days for each resource sampling unit.

VARIABILITY: Macroinvertebrate populations are extremely patchy. Their high variation is both spatial and temporal, resulting from events (e.g., emergence, sudden floods, predation) that may cause entire populations to appear or disappear almost overnight.

PRIMARY PROBLEMS: The major drawbacks of using these organisms as indicators are their extremely patchy spatial and temporal distribution and the labor-intensive preparation, identification, and analysis of invertebrate samples in the laboratory.

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C.6 INDICATOR: Soil and Aquatic Microbial Community Structure

CATEGORY: Response/ Community Structure

STATUS: Research

APPLICATION: Microbial communities are tightly linked to fundamental ecological processes such as decomposition, denitrification, and respiration; they have been used to indicate human influence and are sensitive to the presence of some contaminants (e.g., Ames and Microtox tests); and they can be measured in wetlands where there is no standing water.

INDEX PERIOD: Maximum numbers may be present late in the growing season or as detrital biomass is maximized.

MEASUREMENTS: The most common methods used to identify aquatic microbial communities involve processing water samples through a membrane filter and growing the filtered bacteria on a selective medium. Sediment communities have been examined in extracts prepared from sediment cores and on agar plates prepared with soil suspensions.

VARIABILITY: Temporal variability of microbial community structure during the index period may be high according to normal hydrologic variation; spatial variability should be moderate in most resource sampling units.

PRIMARY PROBLEMS: Microbiological methods for isolation, characterization, and identification of organisms in nature are still not well defined. Microorganisms can develop tolerances to concentrations of pollutants that were once toxic. Microbiological methods are known but are time-consuming and costly.

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C.7 INDICATOR: Nutrients in Water and Sediments

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: High-Priority Research

APPLICATION: Despite widespread concern when cultural eutrophication renders lakes and ponds unsuitable for recreational use, the public generally does not recognize this potential problem in wetlands, nor the relationship between the symptoms of eutrophication and the ability of wetlands to remove nutrients before they reach lakes and ponds. Many studies throughout the United States have documented nutrient concentrations in "reference" wetlands and in wetlands exposed to urban and agricultural runoff and sewage, but these data have not been compiled or synthesized. If this were to be accomplished, it could strengthen the potential to link nutrient concentrations to response indicators.

INDEX PERIOD: An optimal period to sample nutrients in the sediment and aquatic environment would be in mid-growing season, when metabolic and assimilation rates of aquatic biota are at their peak and ambient concentrations are at minima. For purposes of EMAP, sampling immediately following an extreme rainfall event or drought should be avoided in order to minimize temporal variation that may suggest abnormally high or low concentrations.

MEASUREMENTS: Water and soil samples should be analyzed for total Kjeldahl N (TKN), total P, K, Ca, Mg, Na, and pH, as well as Cl where wastewater contamination is suspected. In situations where the need for additional information on N and P species warrants the additional costs for analysis, NO_x, NH_4, organic N, TKN, PO_4, organic P, and total P should be measured. The resources required to acquire samples are minor, approximately 1 person-hour a site. The laboratory analysis cost for each resource sampling unit, assuming three samples each of surface waters, interstitial water, and soil, will be about $900. Samples of the water column and interstitial waters should be collected on a 2- to 4-year frequency; where significant temporal variation in nutrient concentrations results from climatic pulsing or anthropogenic events, more frequent collection may be needed.

VARIABILITY: The expected spatial variability of nutrient concentrations within a resource sampling unit would produce a range that deviates 100% from the mean value for an element. The variability in soil and water samples taken from different locations might be overcome through the use of composite samples. The expected temporal variability of nutrient concentrations during the index period is associated with hydrologic and climatic fluctuations in surface and rain inputs that can dilute concentrations or introduce significant concentrations with surface inflows, and can also have a range that deviates 100% from the mean value for an element.

PRIMARY PROBLEMS: No problems stand in the way of implementation, except for possible high temporal and spatial variability within a resource sampling unit; however, these can be overcome through composite sampling. There is sufficient experience with methods and interpretation of results that implementation should provide significant results early in the program. The added diagnostic ability that results from the nutrient data should help in interpreting other indicators.

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C.8 INDICATOR: Chemical Contaminants in Water and Sediments

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: Research

APPLICATION: Public awareness of pollutants, especially of carcinogens and airborne contaminants, appears to be rising. Most of the public's concern is concentrated on the effects of pollutants on human health, but there is also considerable acknowledgement of their ecological effects, such as the effects of pesticides on avian reproduction and the effects of oil on birds and mammals. The relatively large amounts of organic matter and organic compounds within many wetland ecosystems increase the likelihood of sorption of man-made organic compounds, thereby improving water quality downstream.

Sediments can be a reservoir for some organic compounds (Smith et al. 1988). Through sediment accretion, wetlands can be significant "sinks" for metals and organic compounds. Limiting measurements of contaminant concentrations to those in the water column may result in serious errors of omission, especially for wetlands, where sediments hold the record of past contamination events.

Few studies have documented contaminant concentrations in wetlands. Because wetlands are potentially important sinks for metals and organic compounds, and because most wetlands (being located at topographically low points) are hydrologically exposed to urban and agricultural runoff, sewage, and other pollutant sources, a data base is needed to assess contaminant exposure to wetland response indicators.

INDEX PERIOD: An optimal period to sample chemical contaminants in a wetland environment would be mid-growing season, when metabolic and assimilation rates of wetland biota are at their peak and ambient concentrations of contaminants are expected to be minimal. For purposes of EMAP, samples should not be collected immediately following an extreme rainfall event, because sampling during extreme events may bias data and show temporal variation that may suggest abnormally high or low concentrations. Where significant temporal variation in contaminant concentrations results from climatic pulsing or anthropogenic events, the index period may need to be restricted.

MEASUREMENTS: Measurements of soil contaminants may be conducted during routine sampling for other indicators with little regard for temporal variation, unless there has been some recent major event that would bias the sample. Soil samples would be a composite of numerous samples to reduce the cost of analyzing replicate samples. At a minimum, the surface (top 10 cm) would be sampled. Where suspected historic activities warrant, a second composite sample would be taken at a depth of 10-20 cm. Composite sampling would minimize the need for duplicate samples.

Water and soil samples should be screened for several of the most common metals and organic compounds and "positives" analyzed further in greater detail. Analyzed in this manner, the laboratory analysis expenses would be about $400 for each resource sampling unit. The sample acquisition costs are minor - approximately 1 person-hour for each sampling unit. Contaminants in the water column may be measured during routine sampling for other indicators on an annual basis or less frequently. Soil samples are important components in ecosystem cycling and must accompany any water analysis for contaminants.

VARIABILITY: The expected spatial variability of chemical contaminants within a resource sampling unit is high, but a specific estimate was not available. The temporal variation of contaminant concentrations is associated with hydrologic and climatic fluctuations in surface and rain inputs that can dilute concentrations or introduce significant concentrations with surface inflows; dissolved oxygen status, plant uptake rates, and microbial process rates also influence temporal variations in ambient concentrations. The expected coefficient of variation (CV) of chemical contaminants during the index period is high, at least 50%. An example is provided by Oberts and Osgood (1988), who monitored Pb concentrations in a wastewater treatment wetland for three months during autumn; they found total Pb in base water flow had a CV of 35%, whereas the Pb distribution for total flow from the same wetland had a CV of 133%. Another example by Nixon and Lee (1986) revealed a freshwater tidal wetland that exhibited a three-month CV (based on import/export values) for several elements, as follows: Cu = 73%, Cd = 79%, Ni = 50%, Pb = 106%, and Zn = 446%.

PRIMARY PROBLEMS: No major problems prevent regional implementation, except the high temporal and spatial variability of chemical contamination. Implementation should be preceded by a discussion of the trade-off between the expense of replicate samples and the potential for erroneous results through the use of composite samples. There is sufficient experience with methods and interpretation of results that significant results could occur soon after implementation.

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C.9 INDICATOR: Hydroperiod

CATEGORY: Exposure and Habitat/ Habitat

STATUS: High-Priority Research

APPLICATION: "Hydrology is probably the single most important determinant for the establishment and maintenance of specific types of wetlands and wetland processes" (Mitsch and Gosselink 1986, p. 55). Change in wetland hydrology or hydroperiod is probably the most common impact associated with human alteration of the landscape. Ecosystem-level responses to an altered hydroperiod are changes in species composition, habitat quality, and water storage capacity, among others (Zimmerman 1988). Because hydrologic conditions affect nutrient availability, soil oxygen and salinity, sediment properties, pH, and species composition (Mitsch and Gosselink 1986), changes in hydroperiod can bring about changes in nearly all other components of wetlands, both abiotic and biotic.

Hydroperiod is interpolated from water-level records and can be reported as total number of days of inundation a year. Also of value, where water levels exhibit greater fluctuation, is the number of continuous days of inundation. Temporal variation of high- and low-water events may also indicate hydrological alteration. Hydroperiod is determined by factors outside the wetland, both natural (e.g., precipitation patterns) and anthropogenic (e.g., urban and agricultural development). Changes in hydroperiod may cause, but are not necessarily symptomatic of, changes within the wetland. Thus, monitoring hydroperiod can indicate changes originating in the landscape surrounding the wetland, and to a lesser degree, changes originating within the wetland.

Changes in hydroperiod can indicate changes in habitat. Habitat quality is related to vegetative community composition and distribution, which in turn are profoundly influenced by hydroperiod and by the quantity and quality of incoming water. The measurement of hydroperiod is also essential for interpretation of most of the other indicators. Movement of nutrients in wetlands is primarily via water, so an assessment of hydrology is important for testing relationships of nutrient budgets (Gosselink and Turner 1978, cited in Kadlec 1984).

INDEX PERIOD: Because hydroperiod varies from year to year with changes in rainfall, surface inputs from runoff and streams, and groundwater levels and because water levels fluctuate seasonally within most wetlands, the index period required to identify subnominal hydroperiods is extremely variable. Some classes of wetlands exhibit very little variation in water levels throughout the year and may exhibit yearly changes that result only from yearly variation in precipitation. Water level data in these wetlands may need to be gathered on a semiannual or bimonthly frequency.

MEASUREMENTS: Hydroperiod can be monitored by measuring surface water level, either with continuous water-level recorders or with staff gauges read at regular intervals. Measurement of rainfall at the wetland site, essential in early phases of implementation, may be eliminated during later phases as background data are accumulated and analyzed. In addition to water levels, precipitation measured at the resource sampling unit in most circumstances will provide additional diagnostic information. Precipitation can also be monitored by using rain gauges or data from a nearby weather station.

Water level data should be monitored by using staff gauges. For wetlands that exhibit a much wider fluctuation in water levels on a daily, weekly, or monthly basis, continuous water level recording devices should be used to obtain data of much finer resolution to ensure that fluctuations are adequately represented. Instrumentation will cost approximately $2000 per resource sampling unit for continuous monitoring systems and about 12 person-days a year for each resource sampling unit for data recovery, entry, and analysis. If staff gauges are used monthly, instrumentation will cost approximately $200 a resource sampling unit and require about 12 person-days a year for each site for data recovery, entry, and analysis.

VARIABILITY: The spatial variability in hydroperiod within a resource sampling unit depends on the variability of ground surface elevations. Resource sampling units with significant variation in microtopographic relief will have numerous locations that have hydroperiods that are longer (holes) and shorter (hummocks) than that of the sampling location. Basin-type wetlands often have deep central portions and shallow edges that require careful placement of the water-level measurement apparatus and careful interpretation of data. Within-wetland variability can produce ranges that deviate 100% from the mean value, according to placement of apparatus. However, variability can easily be overcome with experienced placement of monitoring equipment and should not pose serious limitations.

The temporal variability of hydroperiod during the index period can be an important consideration, especially with basin-type wetlands, whose hydrology is determined more by direct rainfall than by runoff or ground water conditions; ranges may deviate 50% from the mean value. With proper corroborating data, climate-driven variation can be accounted for, and temporal variation should not pose serious limitations.

PRIMARY PROBLEMS: There are no significant problems with implementation of hydroperiod as a habitat indicator. Hydroperiods are more accurately known for some wetland types than for others.

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C.10 INDICATOR: Bioassays

CATEGORY: Exposure and Habitat/ Bioassays

STATUS: Research

APPLICATION: One of the recognized functions of wetlands is their ability to filter pollutants from point and nonpoint sources. Excessive pollutant loading, however, can overwhelm the assimilative capacity of wetlands and result in degradation of their biological integrity. The ability of wetlands to sustain healthy organisms can indicate the degree of wetland contamination. Bioassays involve placing an organism or population in the field or into "microcosms" constructed with materials from the field to be tested in the laboratory. Responses of the organism are observed and recorded.

INDEX PERIOD: An optimal period to observe organisms in a wetland environment would be in mid-growing season, when metabolic and assimilation rates of aquatic biota are at their peak.

MEASUREMENTS: Methods entail either collection of soil and water samples in the field for controlled bioassays in the laboratory or the introduction of organisms into some type of constraining environment in the field for later retrieval.

VARIABILITY: The expected spatial and temporal variability of bioassay measures within a resource sampling unit and during the index period, respectively, were not estimated because specific bioassays were not recommended at this time.

PRIMARY PROBLEMS: Much work is needed on developing protocol and target species for wetland communities. Bioassays would not be useful for detecting changes in wetland community structure, because they commonly test a single species at a time, without regard to effects on biotic competition. They would not be useful for testing effects of stressors such as hydroperiod, whose ecological effects are mainly indirect and time-lagged.

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C.11 INDICATOR: Chemical Contaminants in Tissues

CATEGORY: Exposure-Habitat/ Tissue Concentrations

STATUS: Research

APPLICATION: Bioaccumulation integrates the level of contaminant exposure within the recent past. The longer lived the organisms chosen as indicators, the greater the period of time over which the exposure is integrated (all other things being equal). Measurements of bioaccumulation would be as an indicator of contaminant dose to an organism to help explain why wetland response indicators are in subnominal condition.

The bioaccumulation of contaminants (especially metals and pesticides) in aquatic organisms has been studied for many years (see Cairns and Dickson 1980; Hellawell 1986; review by Phillips 1980).

INDEX PERIOD: An optimal period to measure chemical contaminants in tissues would be in mid-growing season, when metabolic and assimilation rates of wetland biota are at their peak.

MEASUREMENTS: Methods for analysis of tissue samples are well developed. The choice of organism is greatly dependent on the pollutant. There are many species-specific differences regarding bioaccumulation of metals and organics. All higher organisms are potential candidates for bioaccumulation sampling, although for consistency and the assurance of an adequate sample size, macrophytes, macroinvertebrates, fish, and herpetofauna are the most likely candidates. Birds and mammals, however, should not be entirely ruled out. A sufficient sample size is required to overcome limitations imposed by within-population variability. This suggests that species with large populations be chosen as indicators. In summary, organisms that are selected should be ubiquitous, relatively immobile, and able to bioaccumulate a large variety of anthropomorphic substances. Determination of bioaccumulation in floral and faunal tissues may be the most costly of indicators if sample collection and processing are included.

VARIABILITY: The expected spatial variability in measuring tissue residues within the same sampling unit is high. Many factors can affect tissue concentrations, not the least of which is the age and diet of an individual organism compared with others in the sample. Also of potential significance is mobility of some species, which may have high or low tissue concentrations resulting from travels or life stages spent in other parts of the landscape. The expected temporal variability of measurements during the index period can be significant.

PRIMARY PROBLEMS: The biggest problems associated with the use of bioaccumulation as an indicator are determination of which species to use and interpreting the ecological implications of the data. Mollusks, certain insects, and macroinvertebrates have been suggested by various authors.

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APPENDIX D: INDICATOR FACT SHEETS FOR FORESTS

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D.1 INDICATOR: Tree Growth Efficiency

CATEGORY: Response/ Population Structure

STATUS: High-Priority Research

APPLICATION: The productivity and sustainability of trees are endpoints of concern. Tree growth efficiency is a response indicator that is related to those two environmental values; it reflects the ability of trees to maintain a healthy and productive presence in an ecosystem. It is related to productivity in that higher growth efficiency is associated with higher gross growth per unit of capacity for growth (e.g., Waring and Schlesinger 1985). It is related to sustainability in that higher growth efficiency is associated with higher resistance to insect attack (Mitchell et al. 1983).

The rationale for incorporating a growth efficiency indicator is based on carbon allocation patterns in trees. Carbon allocation to stem-wood and protective chemicals has lower priority, physiologically, in comparison to allocation to storage reserves, new foliage, and roots (Waring and Pitman 1985). This means that effects of environmental stresses that alter carbon allocation are manifested first in reduced stem-wood growth and in reduced production of protective chemicals (See also E.1, Vegetation Biomass). Stem-wood growth is used in the indicator, rather than amount of protective chemicals, because it is easier to measure wood growth (See also E.7, Dendrochronology: Trees and Shrubs).

Growth efficiency can be estimated by several functions because growth, and capacity for growth, can be measured in several ways. We consider the family of functions that normalize the amount of stem-wood produced to the amount of light intercepted by (or to the leaf area of) the canopy trees. Several forms of the ratio can be recommended for testing. The numerator can be stem-wood volume growth ($m^3\ ha^{-1}\ yr^{-1}$) or biomass growth ($kg\ ha^{-1}\ yr^{-1}$); these values are derived from repeated measurements of tree dimensions at specific locations. The denominator can be one of several indices of the amount of light absorbed by the overstory trees at that same location; candidate indices include leaf area index (LAI), sapwood basal area, fraction of photosynthetically active radiation absorbed by the canopy (%APAR) and the normalized difference vegetation index (NDVI).

Conversions among the various expressions of growth efficiency require estimates of stem-wood specific gravity, the canopy light extinction coefficient, canopy reflectance in specific wavelengths, and/or leaf area-to-sapwood area ratio. The various expressions differ in relative accuracy, precision, cost, and applicability to the EMAP design.

For application as a response indicator, it is possible to derive initial estimates of threshold values for subnominal growth efficiency based on values from the literature. However, these are reported as a variety of units, and conversions to standard units are not always possible. Reports are also usually made on an individual-tree basis rather than on an areal basis. Experience and testing will improve these estimates over time.

While growth efficiency changes indicate changing productivity and sustainability, there are situations where productivity and sustainability may change without a change in growth efficiency. For example, a forest may lose foliage (denominator decreases) and grow slower (numerator decreases) at the same time. Clearly, these changes would be of interest; it has been suggested that we explore the application of the numerator alone, and denominator alone, as independent response indicators. No action has been taken on this suggestion for this document because early reviewers felt that because foliage loss precedes growth reductions, growth efficiency alone would suffice. The suggestion will be reevaluated because it cannot be guaranteed that these subtle differences in timing would be detectable in the sampling design envisioned by EMAP. Thus, both the numerator and denominator will be considered as separate indicators in the future.

Changes in growth efficiency over regional populations may occur for a variety of reasons, and not all of them are of regulatory concern. For example, if the regional population is aging, the regional growth efficiency would decline over time. Although these changes would suggest increased probability of, for example, regional insect outbreaks, or decreased regional growth rates, they would not normally be of concern at a specific location. To interpret the growth efficiency indicator at a specific location, auxiliary information about stand species composition, age, stand density, and other features is required.

INDEX PERIOD: Stem-wood growth and foliage dynamics follow well-known annual cycles, and measurements during the period of most rapid changes from spring through mid- summer should be avoided. Ideally, stem-wood growth would be measured during the dormant season, but foliage measurements would be unreliable at that time. A logistically efficient compromise is to make both measurements during a mid- to late-summer index period, when new foliage is fully expanded but old foliage is not yet senescing.

MEASUREMENTS: The measurements would vary, depending on the form of the function used to estimate growth efficiency. To utilize volume growth in the numerator, tree heights and stem diameters are measured periodically on permanent plots by using standard mensurational techniques (e.g., Husch et al. 1972). These measurements are converted to volume estimates, again by standard methods (Husch et al. 1972). To utilize biomass growth in the numerator, it is necessary to convert volume to weight. The most straightforward method is to use species-specific constants of wood specific gravity, but more accurate methods are possible if additional measurements are made on the resource sampling unit. Another technique utilizes allometric equations based on tree stem diameter and (sometimes) height to estimate stem-wood weight directly. The estimated resource required is two technician-days. The measurement error of 5- to 10-year gross stem-wood volume growth is estimated to have a coefficient of variation (CV) of about 10% when typical forest inventory procedures are used. The recommended interannual sampling frequency is 10 years.

The denominator may be estimated from field (ground-based) or remotely sensed data. One difference between field and remote measurements is that the remote measurements can include vegetation other than overstory trees, whereas the field measurements consider only the vegetation above the instrument. After several alternatives were reviewed, one nondestructive method for each general approach was selected for discussion.

(1) Remotely sensed data. NDVI is an index of LAI in coniferous forests that is obtained by ratioing channel 1 (infrared) wavelengths and channel 2 (red) wavelengths from the Advanced Very High Resolution Radiometer (AVHRR) sensor on the NOAA meteorological satellite (e.g., Running and Nemani 1988). As a measure of light absorption, NDVI is correlated with net primary productivity (Tucker and Sellers 1986). The AVHRR provides daily coverage at 1.1-km nominal resolution, an appropriate scale for regional vegetation analysis. The actual resolution at the edge of the field of vision is less, but better resolution may be possible with future developments in remote sensing technology. Daily coverage provides an opportunity to monitor canopy phenology over the growing season, and this could improve estimates of growth capacity. Plot designs for obtaining the numerator of the growth efficiency indicator should consider the relatively low resolution of AVHRR data. Unprocessed AVHRR data for the contiguous United States costs about $100. The measurement error of satellite-based methods was not estimated.

(2) Field data. Hand-held devices are available (e.g., Decagon Devices, Inc., Li-Cor, Inc.) to measure instantaneous fluxes of photosynthetically active radiation (PAR, ca. 400-700 nm) quickly and easily. The ratio of PAR under a forest canopy to ambient PAR (e.g., in a clearing) is the percentage of PAR absorbed by the canopy (%APAR). %APAR has been tested as a measure of leaf area index over ranges of LAI, stand density, and solar illumination angle, and the results suggest that %APAR may be a widely applicable index of LAI (e.g., Pierce and Running 1988). It seems less likely that canopy phenology can be conveniently monitored by APAR methods. The measurement error of %APAR can be estimated with a CV of <5% in good conditions, but the CV can be much higher in poor conditions (see below). The measurements may be made

directly on a forest plot in about two man-hours. The estimated cost of the APAR measurement devices ranges from $1500 to $6500; field measurements would take two technician-hours per resource sampling unit. The recommended interannual sampling frequency is 1 to 5 years.

VARIABILITY: The expected spatial variability of growth efficiency within a homogeneous resource sampling unit should be less than 15%. The expected temporal variability within the index period would produce a range that deviates <5% of the mean value.

PRIMARY PROBLEMS: (1) Volume and biomass growth estimates: The accuracy of standard procedures may be less than is required for accurate monitoring, and although more accurate methods exist, they are far more expensive. (2) %APAR: Using current techniques, good estimates require clear or uniformly overcast weather and the availability of open clearings near the sampled forest stand. (3) Light absorption, in general: Remote sensing methods are the most promising, but they have not been calibrated across the country, and they require further development. The available imagery from AVHRR works well on flat terrain, but has not been proven to work well on hilly or mountainous terrain, or where the forest stands are intermittent because of rock outcrops and disturbances. Clear-cut and young regeneration areas in coniferous forest areas are usually dominated by broadleaf species that have spectral properties different from conifers.

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D.2 INDICATOR: Visual Symptoms of Foliar Damage: Trees

CATEGORY: Response/ Gross Pathology
Exposure and Habitat/ Pathogens

STATUS: High-Priority Research

APPLICATION: Observations and measurements of visual symptoms and tree mortality identify conditions and agents directly related to forest health. Measures of visual symptoms provide a response indicator for the environmental values of productivity and aesthetics, and they provide exposure and habitat variables for analyses to suggest possible causes of forest condition changes. Visual symptom measurements should be developed on a regional basis to be consistent with regional tree species, pests and pathogens, and environmental features. The measurements may be adapted to different sampling frequencies and densities as required by the heterogeneity of regional forests or by the degree of resolution needed.

The response indicator described in Measurements enables interspecific comparisons and international communications concerning forest health. This "European method" (UNEP and UN-ECE 1987), based on apparent defoliation, has been used in investigations of visual symptoms in Europe and in Canada, but visual symptom monitoring can be conducted differently by other methods. For example "crown density" and "transparency" are measurement methods which have been developed to measure the amount of foliage on loblolly pines and shortleaf pines (Anderson and Belanger 1986) and sugar maple and other hardwoods (Millers and Lachance 1989), respectively.

"Indicator plant" observations are suggested for many visual damage surveys. Tree species can be ranked according to relative pollutant sensitivity by looking at visual symptoms of damage, and indicator plants in the understory can be used to signal exposure of the forest to specific pollutants. An example of this process is the ranking of sensitivity of woody plants to sulfur dioxide and photochemical oxidants (Davis and Wilhour 1976). A positive damage measurement could indicate presence of a pollutant above a threshold exposure, as in the case of the National Park Service milkweed survey (Bennett and Stolte 1985). Indicator plants may be useful in general identification of forest damage related to exposure to ethylene, ozone, peroxyacetyl nitrate, fluorides, sulfur dioxide, chlorides, and nutrient deficiencies. Further diagnostic evaluations of pollutant damage would require more intensive investigations. Because the indicator plants are actual components of the forest ecosystem, as well as indicators of possible damage to other species, they could be viewed as both exposure indicators and response indicators.

INDEX PERIOD: Most damage assessments occur in mid to late growing season (July through September), but some pest surveys are conducted earlier or later to more easily locate and identify a particular pest. For a synoptic survey such as EMAP, mid to late growing season is appropriate (Alexander and Carlson 1989), because the measurements should be made within the active growing season after the first flush of needles or leaves have fully expanded and prior to fall discoloration.

MEASUREMENTS: Plot measurements made at each resource sampling unit include elevation, slope, aspect, stand disturbance, and air pollution indicator plants (e.g., Skelly et al. 1989). The measurements made on dominant and codominant trees at the plot are species, diameter, crown ratio (estimated), crown class, discoloration, defoliation (and/or transparency, and/or crown density), crown dieback, and identified insects and pathogens. A smaller sample of trees are selected off-plot for measurements which require destructive sampling. The measurements on these trees are height, height to live crown, defoliation, crown density or transparency, diameter, annual increment from cores, main-stem injury type and location, crown-needle retention, crown dieback, branch-needle retention, branch-needle length, branch-twig symptoms, branch-discoloration type, root signs, and root symptoms. Root samples are cultured to screen for particular fungi. These measurements are described in detail in the National Vegetation Survey Project Manual for the Visual Damage Survey (Alexander and Carlson 1989), which was developed from a United Nations initiative (UNEP and UN-ECE 1987) and the National Acid Precipitation Assessment Program Forest Response Program (Millers and Miller-Weeks 1986; Zedaker and Nicholas 1986), and other sources.

The European method involves ocular estimation of the proportion of foliage which is present on a tree relative to a standard which is an ideal, fully foliated tree of the same species. Training, experience, photographs of fully foliated trees, and the sample tree itself with imagined full foliage are the basis for defining and maintaining the standard. The transparency and crown density methods, in contrast, are objective methods of determining the area of the tree crown which is without branches or leaves. Transparency and crown density give a measure of the amount of foliage that is actually on the tree, without reference to the foliage condition expected of an ideal, healthy tree.

The European method requires considerable training, skill, and field measurement time to enable crews to determine the subjective estimate of defoliation repeatedly within a 10% range. The transparency and crown density methods are considered to be easier to accomplish in the field and would be expected to be more repeatable in determining a more objective value.

Interspecific comparability is another important issue to consider. The European method results in a value which could be called "fraction of foliage absent relative to that of a healthy tree." With acceptance of the UN-ECE convention for assessment (UNEP and UN-ECE 1987) this value is theoretically comparable with the values obtained from measurements of other tree species. The transparency and crown density methods result in an absolute value which is not comparable with other tree species. For example, the normal transparency or crown density of white ash or loblolly pine is much different than the normal transparency or density of sugar maple or western hemlock. Comparison between species would require that the values of each would have to be normalized with respect to "normal transparency" for each species.

The estimated measurement error for all visual measures associated with this indicator is 10%.

In addition to field measurements, further sources of information within the U.S. Department of Agriculture-Forest Service (USDA-FS) include Forest Pest Management and Forest Inventory and Analysis programs. These programs obtain mortality data during routine inventories and conduct special detection and evaluation surveys of forests which could be statistically linked to the EMAP monitoring design.

The measurement error for each of the different metrics may be determined by accessing Visual Damage Survey data from the 1988 and 1989 tests conducted by the USDA-FS National Vegetation Survey and the North American Sugar Maple Decline Project. Many of these data are the "presence-absence" type of data. Training, experience, and effective quality assurance and quality control programs are essential and effective in obtaining high-quality data (Alexander 1990; Burkman 1990).

VARIABILITY: A summary index of response is based on percentages of defoliation and discoloration. The expected spatial variability of the mean summary index within a resource sampling unit would produce a range that deviates <50% from the mean value. The expected temporal variability of the visual index during the index period would produce a range that deviates <20% from the mean value.

PRIMARY PROBLEMS: Standardization of measurement and assessment methods to allow comparability is difficult. The UN-ECE has obtained agreement on protocols from its member countries, but in practice there may be deviation from the standardized techniques. This could be due to different interpretations of the ideal, fully foliated tree which is used as a standard. The assessment convention for health classification is expected to change as information is acquired. Since it is a subjective measurement, consideration should be given to establishing agreement on an objective standard.

Destructive sampling is required for increment core, branch, and root symptom evaluation. Destructive sampling conflicts with permanent plot protocols and should be done outside the field plots within a resource sampling unit.

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D.3 INDICATOR: Nitrogen Export

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: Research

APPLICATION: In most forest communities, disturbances may change the normal patterns of accumulation and cycling of nutrients through vegetation and other forest components (e.g., Bormann et al. 1974; Bormann and Likens 1979; Swank and Waide 1980). Such changes can alter downstream water chemistry (Likens and Bormann 1974; Sollins et al. 1981). Studies of nutrient cycling and loss have emphasized nitrogen for several reasons (Vitousek et al. 1982):

- Nitrogen is the element most often limiting to forest growth.
- Losses of nitrogen often increase more than do losses of other nutrients following disturbance.
- Increased production and loss of nitrate can cause increased solution losses of cation nutrients.
- Increased nitrification can increase rates of nitrous oxide production and volatilization.

Ecosystem-level stability may be gauged by monitoring downstream water quality (O'Neill et al. 1977), particularly nitrate concentrations (Vitousek et al. 1979). Nitrate concentrations in surface water are the products of many site-specific processes (Vitousek et al. 1979, 1982) and of chance occurrences such as wildfire (Grier 1975), insect defoliation (Swank et al. 1981), and animal foraging (Singer et al. 1984). Although disturbances do not necessarily result in altered nitrate concentrations (Vitousek et al. 1982), changes in nitrate concentrations are a "sure sign" of some type of disturbance within the ecosystem.

INDEX PERIOD: An optimal sampling window for measuring nitrogen export rates has not been determined, because nitrogen export tends to be an episodic event.

MEASUREMENTS: To implement this indicator, samples of water (either surface water runoff or ground water) are obtained, and NO_3^- concentration (and possibly other chemicals) is determined by standard laboratory procedures.

VARIABILITY: Because nitrogen export is an integrative measure, the spatial variability of nitrogen export within the resource sampling unit is inconsequential. The expected temporal variability of nitrogen exports throughout the year was not estimated.

PRIMARY PROBLEMS: (1) It has not been possible to identify a suitable index period for the EMAP sampling design, because concentrations can fluctuate rapidly and unpredictably over the season. (2) Continuous monitoring (to characterize total export and to alleviate the problem of index period sampling) is not envisioned by EMAP.

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D.4 INDICATOR: Litter Dynamics

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: Research

APPLICATION: Large quantities of nutrients circulate within a forest ecosystem. Although part of the annual requirements of plants can be met by reabsorption before the loss of tissues, the remaining nutrients must be obtained by uptake from the soil. The majority of soil nutrients is derived from the decomposition of organic litter, including woody material such as limbs, insect frass, and fallen leaves. Thus, litter dynamics such as the rate and pathways of decomposition are important determinants of ecosystem productivity and condition (Waring and Schlesinger 1985).

A potential indicator is the chemical composition of litter and its changes over time as it decomposes. This process can be affected by the chemistry of litter before it falls, by the dynamics of populations of microbes which feed on litter after it falls, and by the abiotic environment. A common index of litter chemistry during decomposition is the ratio of carbon to some other chemical such as lignin, nitrogen, or phosphorous.

INDEX PERIOD: Measurement of litter dynamics during an EMAP-defined index period does not seem possible, because although litter dynamics are useful response indicators over long periods, in the short term they may be too greatly influenced by current weather patterns to allow accurate measurements. It may be possible to place artificial "litter" samples at field locations and return parts of them to the laboratory during an index period each succeeding year. Probably the best sampling period would then be late summer or early autumn.

MEASUREMENTS: Numerous measurements would be considered, for example, the concentrations of nutrients (e.g., N, P, K) and other chemicals (lignin), the moisture content, and microbial activity rates. With artificial samples, loss of dry weight would also be determined.

VARIABILITY: The expected spatial variability of litter dynamics within the resource sampling unit and its temporal variability throughout the year were not estimated.

PRIMARY PROBLEMS: The outstanding problem is the inability to define a practical measurement for a one-time sample during an index period.

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D.5 INDICATOR: Microbial Biomass and Respiration in Soils

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: Research

APPLICATION: Soil organisms have an important role in the retention and release of nutrients and energy transfer in forest ecosystems through processes such as nitrogen fixation; production of hormones, antibiotics, and metal chelator; nutrient cycling; material transfer between plants through mycorrhizal hyphae; and creation and maintenance of soil structure through the production of humic compounds and polysaccharide glues (Perry et al. 1989). When these key biological processes are disrupted, ecosystems become fragile and subject to threshold changes (DeAngelis et al. 1986).

During the initial development of this indicator, measurements of key soil biological variables would be used to establish baseline status in terms of the presence and distribution of soil flora and fauna with respect to other soil variables that are being measured (see indicator D.8, Soil Productivity Index). All such constituents would be evaluated in relation to forest condition.

The component variables of interest may vary widely across different forested regions of the United States, but initially are defined to include the measurement of variables relating to (1) soil microbial biomass, (2) soil respiration, and (3) mycorrhizal fungi. Soil microbial biomass is defined as the living part of the soil organic matter, excluding plant roots and soil fauna larger than 5000 μm^3 (Jenkinson and Ladd 1981). Soil respiration is defined as an energy-consuming process including the uptake of oxygen and/or the release of carbon dioxide by living, metabolizing entities in the soil (Anderson 1982). Soil mycorrhizal fungi can be characterized by observing the functional types of mycorrhizae (e.g., obligatory or facultative) on the tips of roots collected as part of the microbial biomass sampling. If there is a shift in type, there is likely to be a resulting change in forest response.

Soil biological data can also contribute diagnostic information by indicating possible mechanisms and causes of subnominal forest condition. The most promising interpretations of ecosystem biological processes would consider both soil and vegetative productivity as inputs.

INDEX PERIOD: The optimal index period for sampling is late June through early September for the mid-latitude forests of the United States. Soil biological sampling for a given plot should be performed at the same interval of the index period during each repeat visit. Also, soil biological sampling should be performed concurrently with the soil and foliar productivity sampling at a given plot.

MEASUREMENTS: Soil biological data can be obtained by field excavation of soil core samples followed by laboratory characterization of the types and amounts of biota present. For the determination of soil microbial biomass by chloroform fumigation, the core samples will be processed according to procedures defined by Vance et al. (1987), which are based on methodology outlined in a series of papers by Jenkinson and Powlson (1976a,b) and summarized by Parkinson and Paul (1982). (See also indicator F.3, Microbial Biomass in Soils.) For the determination of soil respiration rates, the samples would be handled according to procedures similar to those described by Anderson (1982). For the determination of soil mycorrhizal fungi, a number of methods exist, but none have been positively identified for their appropriateness in EMAP.

Estimates of measurement error for each analytical parameter may be derived by accessing existing soil biological data that satisfied stringent quality assurance criteria. For microbial biomass, an average CV of ≤15% is typical for replicate samples in agricultural assay work (Vance et al. 1987). The laboratory bias is expected to be ≤10% of the reference value. For the sample measurement system as a whole (e.g., sampling, preparation, and analysis), an average CV of 30% or less is likely. Collection of soil for two composite samples per resource sampling unit would require 0.5-0.7 h.

VARIABILITY: The expected spatial variability of soil biological measures within a resource sampling unit would produce a range that deviates <50% of the mean value. A significant amount of soil spatial variability also could be present at any given plot within the sampling unit. Uncertainty in the soil biological data at a plot can be greatly reduced, however, by the use of a "composite" or "transect" sample design that can accommodate within-plot differences in soil characteristics.

It is anticipated that a design could be adopted whereby the samples that are collected will control the within-plot uncertainty to a level that is (1) less than the measurement system uncertainty and (2) negligible with respect to the regional soil aggregation variability (Taylor 1987). The resulting high level of data quality would allow the data users to focus on discerning "real" temporal changes in soil biological processes within a highly variable population framework.

PRIMARY PROBLEMS: This indicator has tremendous potential for establishing linkages between the various exposure and response core indicators. However, most of the work that has been undertaken to date has been for research purposes and may not be amenable to implementation in a large-scale program such as EMAP. Relationships among the individual variables are less than well defined. Because of the potential for large spatial variability of soils within and among forest plots and the unavoidable necessity of performing destructive sampling to collect soil biological samples, a rigorous sample design must be developed. Because of the richness of species that compose the soil flora and fauna, it would probably be necessary to identify species diversity in the samples that are collected to help discern and interpret the categorical quantitative changes reflected in microbial biomass measurements. Temporal changes in the balance of soil flora and fauna can provide an early indication of microbial population shifts or other changes in ecosystem function.

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D.6 INDICATOR: Nutrients in Tree Foliage

CATEGORY: Exposure and Habitat/ Tissue Concentrations

STATUS: High-Priority Research

APPLICATION: The relative proportions and concentrations of foliar nutrients may indicate possible mechanisms and causes of abnormal forest condition. Individual nutrient concentrations and their ratios could be applied to development of threshold or critical levels. Foliar nutrient measurements would enable establishment of baselines, comparisons of element ratios, and correlations with other measured indicators such as radial growth, height growth, visual symptoms, and atmospheric deposition gradients (Ke 1989; Landolt et al. 1989).

INDEX PERIOD: The optimal index period depends on the selected measurement option (see Measurements). Fresh foliage (Option 1 below) would be sampled in late summer. Ideally, hardwood samples would be taken late in the growing season but at least two weeks before the onset of autumn coloration, and conifer samples would be taken during the dormant season. Litter (Option 2) would be sampled in early autumn; litter traps must be deployed in the summer and revisited after leaf senescence but before winter snow.

MEASUREMENTS: There are two possible approaches for sampling foliar nutrients which differ in time of year and cost. The less expensive option involves sampling litter rather than fresh foliage.

Option 1: The branch samples taken for needle retention measurements (see indicator D.2, Visual Symptoms of Foliar Damage) would also be used for foliar analysis. Hardwood leaf samples must be taken specifically for this purpose. Where possible, at least two samples each will be taken of healthy and symptomatic leaves. Procedures described in the Acid Rain National Early Warning System Manual on Plot Establishment and Monitoring (Morrison 1988) would be followed to obtain foliar concentrations of N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, Na, B, and Al. The collection, handling, and laboratory work involved in foliar analysis will cost approximately $65 per sample, not including travel and per diem costs.

Option 2: Samples of the current year's needles and leaves would be collected prior to snowfall in autumn by placing an appropriate litter trap in the field. The samples would be processed in the laboratory in the same as fashion described in Option 1. In this case, the cost of sample collection and analysis is about $35 per sample.

Samples should be taken from trees very close to the permanent field plots. Fresh foliage should be composited by species for analysis. Litter samples may be obtained directly on the permanent plot, but separation of foliage by species may not be practical. Under both options, a subsample could be oven-dried, ground, and stored frozen under a vacuum for later analysis. The cost of archiving samples has not been determined. The estimated laboratory measurement error is 5% for all elements.

VARIABILITY: The expected spatial variability of nutrient concentrations within a resource sampling unit would produce a range that deviates <50% of the mean value. The expected temporal variability of these indicators during the index period would produce a range that deviates <80% of the mean value.

PRIMARY PROBLEMS: Existing laboratories would probably require special instruction to perform analyses with lower measurement error than is required for routine crop and horticultural analyses.

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D.7 INDICATOR: Chemical Contaminants in Tree Foliage

CATEGORY: Exposure and Habitat/ Tissue Concentrations

STATUS: High-Priority Research

APPLICATION: Like nutrients (D.5), the amount and concentrations of foliar contaminants may indicate possible mechanisms and causes of abnormal forest condition. Two applications of this indicator are anticipated. First, at approximately 10% of the field plots within a resource sampling unit, a comprehensive list of contaminants would be measured in order to assay and survey the presence of toxins. Second, upon identification of suspect pollutants, specific archived foliage samples would be analyzed for concentrations of particular chemicals from specific plots.

INDEX PERIOD: Because toxin measurements would be conducted on a subset of the foliage samples that are collected for foliar nutrients analyses, the sampling period is the same as the Nutrients in Tree Foliage indicator (D.5).

MEASUREMENTS: Some example compounds can be inferred from a review of similar protocols from other monitoring programs. Measurements of potential exposure indicators have been incorporated in the European monitoring systems. The United Nations (UNEP and UN-ECE 1987) recommends analysis of F, Cl, Cd, and Pb concentrations. The Swedish monitoring system measures concentrations of S, As, V, Cr, Ni, Cu, Zn, Cd, Hg, and Pb in moss on intensive representative plots (SNV 1985). Northern European countries recommend monitoring Pb, Cr, Cu, and Cd in the organic debris and humus (Nordic Council of Ministers 1988).

See the Nutrients in Tree Foliage indicator (D.5) for field collection costs; laboratory analysis costs for various toxins have not been estimated. The estimated laboratory measurement error is 5% for all elements.

VARIABILITY: The expected spatial variability of chemical contaminants in foliage within a resource sample unit would produce a range that deviates <50% from the mean values. The expected temporal variability of these indicators during the index period would produce a range that deviates <80% of the mean values.

PRIMARY PROBLEMS: The possible decay or transformation of chemicals in archived samples is a concern.

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D.8 INDICATOR: Soil Productivity Index

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: High-Priority Research

APPLICATION: Soil productivity is generally defined as the capacity of a given volume of soil to produce a vegetative response under a specified system of management (SEA-AR 1981). Initial measurements of key soil productivity variables will be used to establish baseline levels and ratios among physical, chemical, and biological soil constituents in relation to nominal and subnominal condition as estimated by response indicators. Periodic remeasurement of these variables will be used to assess trends that might show increases or decreases in value over time.

The specific parameters of interest will vary among forested regions of the United States. Generally speaking, they will include specific soil nutrients (see indicator D.5), toxic substances (see indicator D.6), erodibility factors, soil structural characteristics, parent materials, and ancillary data such as soil moisture supply (e.g., Palmer Drought Index). Soil productivity data provide interpretive information that is not available through foliar chemical analysis because plants may compensate for limited soil nutrients and moisture.

Forest productivity can be affected by chronic or acute deficiencies of essential soil nutrients needed for plant growth. Productivity can also be disrupted by changes in the populations of microorganisms that are essential to biological cycling processes within the forest floor. These effects may be caused by long-term natural perturbations or short-term changes due to human intervention. For example, whole-tree harvesting in commercial forests can cause changes in macronutrient cycling (e.g., potassium). A low ambient level of magnesium in some forest soils is an example of a naturally occurring stress that could be aggravated by certain management practices (Ballard and Carter 1985). Forest floor disturbances can interfere with nitrogen cycling (Peterson et al. 1984), and the effects of burning (Debano and Klopatek 1988) and disruption of the soil mycorrhizal fungi on tree roots (Vogt and Persson 1990) are other examples of stresses in forest soils.

Soil productivity can be adversely affected by the presence of toxic substances and contaminants in the soil. This presence indicates exposure to potentially detrimental chemical compounds and elements possibly resulting from land use practices (e.g., application of pesticides, mineral extraction), atmospheric deposition (e.g. sulfur in acid precipitation), or naturally occurring phenomena (e.g., overabundance of magnesium in serpentine parent materials).

Plant metabolic processes are disrupted by toxicity or contamination in at least two ways; the plants may be (1) directly affected through uptake of the substances, and (2) indirectly affected through an associated decrease in soil nutrient availability. In the first case, substances taken up by plants can affect physiological processes and internal physical structure (McLaughlin 1985). This lowers the rate of photosynthesis, growth, and resistance to secondary stresses (McLaughlin 1985; Miller 1983). In the second case, mobile substances bind with soil nutrients and migrate to lower soil horizons, decreasing plant nutrient availability.

Chemical toxicity can also reduce the number and variety of soil decomposer microorganisms, thereby decreasing the rate at which nutrients become available for plant uptake (Verein Deutscher Ingenieure Commission for Air Pollution 1987) and effectively lowering the site productivity. This has implications for management of mineral extraction, pesticide applications, and atmospheric emissions. Because the degree of toxic effects on plant tissues and growth is related to the duration of exposure, concentration, exposure regime, and chemical dynamics of the ecosystem, initial discovery of such substances in the soil can signal the need for closer monitoring of exposed ecosystems.

INDEX PERIOD: No optimum index period exists because of the relatively low (<10%) temporal variability of most soil nutrient concentrations during the late spring to early autumn sampling window for the mid-latitude forests of the United States. However, any given field plot should be sampled at about the same time during the index period. Also, soil characterization and sampling should be done concurrently with the foliar sampling and tree measurements at a given plot.

MEASUREMENTS: Soil classification data can be obtained from existing soil survey information or by on-site soil excavation and characterization. Soils on unmapped plots should be mapped to the soil series level according to accepted National Cooperative Soil Survey standards. Each plot should be thoroughly characterized for physical soil and landform features while at the field site.

Composite soil samples from O, A, E, B, and C master horizons present within the resource sampling units would be obtained once every four years. The soil physical and chemical variables of interest for a given region would be analyzed in these samples, and a portion of each sample would be archived for possible analyses in the future. The soils would be sampled according to procedures similar to those described in the Direct-Delayed Research Program field methods manual (Kern et al. 1988) and the ARNEWS manual (Morrison 1988).

Soil samples would be prepared and analyzed according to procedures similar to those described in the Aquatics Effects Research Program soil preparation and analysis methods handbook (Blume et al. 1990) and the Forest Response Program soil analytical methods manual (Robarge and Fernandez 1987). The anticipated suite of laboratory analytical measurements for regions of the eastern United States includes the following.

Soil organic biomass (organic horizons only)
Bulk density
Rock fragment estimation
Particle size analysis (mineral horizons only)
pH in water and in 0.01 M calcium chloride
    Exchangeable Ca, Mg, K, Na, Fe, and Al in 1 M ammonium chloride
    Cation exchange capacity in 1 M ammonium chloride
    Exchangeable acidity in barium chloride triethanolamine
    Mineralizable N by anaerobic incubation
    Extractable P by Bray #1
    Extractable sulfate in water
    Total C, N, and S
    Total Fe, Mn, Cu, Zn, B, and Mo (organic horizons only)
    Total Pb, Cd, Ni, Cr, and V (organic horizons only)

The suite of laboratory analytical measurements for regions of the western United States is under development.

Resources required to characterize and collect field samples include one day per plot for a soil scientist at an estimated cost of $40 per sample. Laboratory preparation expenditures are about $75 per sample, and laboratory analysis costs are approximately $250 per sample.

A coefficient of variation (CV) estimate for each soil analytical parameter may be derived by accessing existing soil survey data that satisfied stringent quality assurance criteria (Byers et al. 1990). For most of the analytical laboratory measurements, an average CV of 10% or less is typical for replicate samples. The expected laboratory bias is 5% or less of the reference value. For the sample measurement system as a whole (e.g., sampling, preparation, and analysis), an average CV of 20% or less is typical.

VARIABILITY: The expected spatial variability of soil productivity within a resource sampling unit would have a range that deviates 80% from the mean values. The expected temporal variability of soil productivity throughout the year would produce a range that deviates <10% from the mean values. It is recognized that a significant amount of soil spatial variability can be present not only within a resource sampling unit, but even within a single plot in that unit. Uncertainty in the soil productivity values at a plot can be greatly reduced, however, by the use of a "composite" sample design that recognizes and accommodates the within-plot differences in soil characteristics. It is anticipated that a design would be adopted whereby the field samples would control the within-plot uncertainty to a level that is (1) less than the measurement system uncertainty and (2) negligible with respect to the regional soil aggregation variability (Taylor 1987).

PRIMARY PROBLEMS: Because of relatively low analyte concentrations in forest soils, existing laboratories will be required to perform the analyses with a higher level of precision and accuracy than is normally required for the more traditional crop and horticultural soil analysis. Because of the potential for large soil spatial variability across a forest plot and the unavoidable necessity of performing destructive sampling to collect soil samples, a rigorous sample design must be developed.

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D.9 INDICATOR: Stable Isotopes

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: Isotopic composition is an exposure indicator that is useful for gross separation of effects due to climate and pollution. Departure from a normal ratio of ^{13}C to ^{12}C in plant tissue is a general integrative index of stress. Once stress is identified, speculation of the probable cause(s) can be made by observing climatic and deposition patterns over a known forest disturbance gradient. If climatic change is involved, alterations in the stable isotopic composition of oxygen and hydrogen in leaves and other plant tissues should be evident in shifts in the $^{18}O/^{16}O$ and the $^{2}H/^{1}H$ ratios.

Air pollutant exposure may be diagnosed in some cases by observing shifts in the isotopic composition of S or N along spatial and temporal gradients (Waring 1990). For example, if the H and O isotopic signatures of weather and tree rings leave no record of major weather changes over the last few decades, but C isotopes indicate closure of leaf pores is constraining photosynthesis, then we would expect to find changing S and/or N isotope ratios in wood cellulose of more recent tree rings. This signal should increase dramatically in trees close to a major source of pollution, as it is known to do in sensitive plants such as epiphytic mosses and lichens (Waring 1988).

In another example, epiphytic lichens and some mosses provide a cumulative record of the isotopic composition of atmospheric S. Protected understory plants tend to take up S almost exclusively from the soil. The use of S isotope data with biological parameters such as areal extent of species helps in assessing the extent to which the system is perturbed by the anthropogenic additions of sulfur (Krouse 1989).

INDEX PERIOD: If the analyses are made from archived samples of foliage and increment cores (see indicator D.2, Visual Symptoms of Foliar Damage: Trees), or other sources, an index period is not applicable.

MEASUREMENTS: There are known natural abundance isotopic compositions of C, H, O, N, and S in ecosystem components. The object is to measure the degree of fractionation (the altering of isotope abundances) of these isotopes in wood cellulose and other plant tissue. A mass spectrometer is required for accurate detection of the small differences in the ratios of heavy to light isotopes ($^{13}C/^{12}C$, $^{18}O/^{16}O$, $^{2}H/^{1}H$, $^{15}N/^{14}N$, and $^{34}S/^{32}S$), and gaseous samples are required for the isotopic determinations. Many combustion schemes have been developed to quantitatively break down diverse molecules into the simple gases most suitable for mass spectrometry. For measurement of $^{13}C/^{12}C$ ratio, see the report by the National Council for Air and Stream Improvement (1989). Current analysis costs range from $30 to $100 per sample through commercial firms (Peterson and Fry 1987). The estimated laboratory measurement error is 5%.

VARIABILITY: The sulfur isotope composition of all components of an ecosystem may be consistent over a large area, yet there could be significant variations in one specimen (Krouse 1989). The expected spatial variability of isotopic ratios within a resource sampling unit would produce a range that deviates <5% from the mean values. The expected temporal variability of the ratios during the index period would produce a range that also deviates <5% from the mean values.

PRIMARY PROBLEMS: This is a promising technique that is perhaps a way to cleanly separate climate- from pollution-caused changes in forest condition, but the technique requires development.

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D.10 INDICATOR: Carbohydrates and Secondary Chemicals in Plants

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: Carbohydrates and secondary chemicals could be utilized to discover changes in allocation of photosynthate or decreasing photosynthetic activity and point to specific stresses that cause certain types of changes in allocation. The rationale for this exposure indicator is that although stress-induced change in one dimension of carbon allocation may be masked by changes in other dimensions, the general result of stress is that resources may be allocated differently. Some of these changes would be detected by other types of gross indicators, for example, "growth." The intention here is to suggest a biochemical analog for carbon allocation, and we would be looking for characteristic changes in the type and amount of chemicals produced under different stresses.

Plants produce a wide variety of secondary metabolites for a variety of purposes, including healants, repellents, and attractants. The term "secondary metabolites" here includes cinnamic acids, alkaloids, flavonoids, phenylpropanoid compounds, phenolic compounds, terpenoid compounds, steroids, and carotenoids. They are produced by five main biosynthetic routes: (1) sugar metabolism, (2) acetate-malonate pathway, (3) acetate-mevalonate pathway, (4) shikimic acid pathway, and (5) as metabolites derived from amino acids.

Although the function of most secondary metabolites is unknown, their complexity of structure is perhaps indicative of a specificity of function that has not yet been discovered. Turnover is often quite rapid for these metabolites, and they are not, in general, storage compounds. Given the complexity of structure and the associated high energy cost associated with biosynthesis of these compounds, it has been suggested that their concentrations could be monitored as a biochemical indicator of stress exposure or response. The rationale is that smaller concentrations may indicate less overall energy is available for producing these metabolites. On the other hand, higher concentrations may indicate that more are "needed" in response to particular stresses. Thus, both high and low concentrations can indicate a stress response. The array of changes in different secondary chemicals may have diagnostic value. Changes in secondary metabolites have been noted in response to most possible stresses, including nutrients, phytohormones, light, temperature, pH, aeration, antibiotics, and microorganisms.

Carbohydrates can be utilized to discover the occurrence of buffering or compensation in response to stress; that is, stresses may drain down ecosystem reserves prior to a response when responses are threshold phenomena. Photosynthesis is the process of converting carbon dioxide and water into carbohydrates and oxygen. Carbohydrates are the precursors of all plant products and are usually the major components of plant cells. Some of the carbohydrates may not be utilized immediately and are stored in various forms until needed. The major forms of storage are sucrose (simple sugar), sucrose-based oligosaccharide (small-chain polymer), starch (polysaccharide of glucose), fructan (polymer of fructose), and mannose-containing polysaccharide. An index of reserves could be constructed by measuring the total energy stored in the major reserve carbohydrates.

INDEX PERIOD: An optimal sampling period is unknown for secondary chemicals, but would depend on metabolite and organism. The period of maximum potential for carbohydrates is usually just prior to spring bud-burst.

MEASUREMENTS: (1) Concentrations of secondary chemicals from various plant parts. Specific plant parts or chemicals have not been determined.

(2) Total concentrations of carbohydrates in various forms in old roots and twigs. Measurement requires laboratory capabilities: solubilization in aqueous solvents or aprotic dipolar organic solvents, freeze-drying or precipitation, and measurement with gas-liquid chromatography or other techniques. Protocols are available for extracting and measuring the concentrations of major storage carbohydrates in plant tissues.

The measurement error is unknown for secondary chemicals, but would depend on metabolite and organism.

VARIABILITY: The expected spatial variability of secondary chemicals within a resource sampling unit and temporal variability during the index period were not estimated.

PRIMARY PROBLEMS: Secondary chemicals are highly variable in space and time and are possibly too responsive to stresses. Some concentrations depend, for example, on whether the sun is shining or not. The relative uniqueness of secondary metabolites confounds comparisons; different metabolites are found in different species of plants, and the function of most secondary chemicals is unknown.

The index period for carbohydrate measurement is subjective (just before a phenological event), and the sampling window is narrow. The reference concentrations can be different for different parts of a plant, and for different species. Carbohydrates are probably highly variable from tree to tree.

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D.11 INDICATOR: Bioassay: Mosses and Lichens

CATEGORY: Exposure and Habitat/ Bioassay

STATUS: Research

APPLICATION: Mosses and lichens can indicate exposure of forest resources to some airborne pollutants. Exposure of forests to airborne pollutants can disrupt ecological processes (e.g., nutrient cycling) and decrease productivity. The degree of ecological impact depends on the toxicity of the compounds, their rate of deposition, and subsequent chemical interactions within the ecosystem. Determining the exposure of forests to particular atmospheric pollutants can identify gradients along which to evaluate effects on forest condition.

Mosses and lichens absorb many elements and compounds from air and precipitation. Thus, they have been used in a number of studies as biomonitors for indicating presence of airborne pollutants (Manning and Feder 1980; Ferry et al. 1973). Whereas known locations of pollutant emitters, coupled with atmospheric circulation models, can suggest areas of exposure to atmospheric pollutants, bioindicators placed systematically in forests can actually demonstrate exposure.

INDEX PERIOD: The uptake of toxic chemicals by forest vegetation is likely to be greatest during the growing season. Thus, exposure of moss or lichen samples to potential pollutants could coincide with this period, mainly spring through summer. If certain atmospheric contaminants are emitted in the winter (e.g., SO_2 from heating), this would not be appropriate.

MEASUREMENTS: To sample forests for exposure to atmospheric deposition of pollutants, moss bags and/or lichen transplants are positioned on forest plots. After 30-day (or other suitable length) exposure periods, accumulated heavy metals are measured, and concentrations are compared with control samples. These measurements yield relative concentrations (mg cm^2 day^{-1}) of heavy metals and allow estimation of exposure gradients.

VARIABILITY: The expected spatial variability of accumulation within a resource sampling unit and its temporal variability during the index period were not estimated.

PRIMARY PROBLEMS: (1) Problems center around determining which areas of the United States should be monitored for heavy metals. Major emitters are required to report emissions to the EPA; however, numerous smaller, but collectively very important, emitters must be considered also. Without a priori information, a systematic grid of sample points is appropriate.

(2) Data from existing atmospheric sampling networks (e.g., EPA Toxic Air Monitoring Study) may help to establish baselines; however, sample stations are usually associated with urban centers. Few data are available with which to determine changes in pollutant concentration over distances away from urban areas. A useful exception is data available from many of the national parks.

(3) The actual relationship between concentration of toxic compounds in the atmosphere and concentration collected by moss and lichens is not clear. Thus, only assessment of relative exposure over time may be possible. Parallel measurements of air toxics (see indicator H.5, Metals and Organics) using sophisticated air sampling apparatus and organic indicators would help calibrate the organic indicators.

(4) Although the effects of airborne toxins on forest vegetation have not been well substantiated, this indicator seems important from the perspective of EMAP's goal to monitor exposure to airborne pollution.

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APPENDIX E: INDICATOR FACT SHEETS FOR ARID LANDS

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E.1 INDICATOR: Vegetation Biomass

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: High-Priority Research

APPLICATION: An important environmental value for arid and semiarid resource classes is the continued productivity of grassland, shrubland, and woodland vegetation. This value includes secondary and higher levels of productivity (animal habitat) as well as primary productivity (vegetative growth). Net primary productivity (NPP), the chemical energy stored or accumulated by vegetation per unit time, is critical to continued ecosystem function. NPP is perhaps the best integrator of ecological response to environmental stresses and perturbations and is among other things dependent upon the lack of major disturbances and resource availability.

When disturbance or levels of change are moderate (i.e., not at the intensity of fire or mechanical disruption), changes in annual NPP will generally precede changes in vegetation structure. When large or moderate disturbances occur, their impact can be judged in part by the recovery of vegetation toward predisturbance levels of NPP. Advances in remote sensing technology and an improved understanding of spectral signatures related to functional properties of plants offer exciting prospects for large-scale assessments of current and potential NPP.

(1) **Vegetation Greenness:** Total plant chlorophyll (green leaf material) is an excellent integrator of NPP in ecosystems, and it can be easily monitored with airborne and satellite remote sensing. Because the acquisition of carbon is among the highest priorities for plants, resource investment in leaves and their constituents is probably pushed to the point where the return on that investment (sunlight capture) is marginal in its effect. Thermodynamic complexities of capturing sunlight and carbon require that the ratio of chlorophyll to other resource-expensive leaf constituents remain within a narrow range. Thus any limitation or impediment to plant resource acquisition and growth is likely to be reflected by a decrease in the total green leaf material (i.e., chlorophyll) deployed by plants.

(2) **Annual Wood Increment:** Because of its ability to provide a historic (i.e., retrospective) record of annual biomass accumulations, this indicator was addressed separately (see Indicator E.8, "Dendrochronology: Trees and Shrubs"). When woody vegetation is present within a sampling unit, one measurement which could give important insight into vegetation response is annual wood increment. Allocation of C to wood is a lower priority than allocation to either leaves and stems for energy capture or roots for mineral nutrient and water acquisition. The earliest and most sensitive reduction in C allocation will occur in wood when environmental stress reduces NPP (see also Indicator D.1, "Tree Growth Efficiency"). Incorporation of trace material into wood and other plant materials can also provide evidence of exposure to growth-inhibiting toxins. In addition, C, H, and O isotope abundances in wood may provide evidence of the state of the stomatal and photosynthetic systems at the time wood is being formed. Measurement of relative woody growth increment requires approximately 0.5 h of technician time per plant. There is a spectral signature for lignin and cellulose (the constituents of wood); thus it may be possible to monitor annual changes in woody biomass remotely.

(3) **Ratio of Root Biomass to Shoot Biomass:** Investment of C to roots versus leaves and stems involves some degree of trade-off. Conditions which tend to restrict a plant's ability to obtain water or mineral nutrients may cause increases in the root/shoot ratio. If above-ground resources, particularly light, are limiting, the root/shoot ratio may decline. Either investment is probably made so that it is efficient at the margin. Although the literature contains numerous studies documenting shifts in C allocation pattern in response to environmental changes, the data often have not been obtained in a manner which allows an economic analysis of investment patterns. This is an area for future research. Nonetheless, comparative measures of

C allocation in exposed versus controlled areas would be an excellent indicator of ecosystem function and health.

MEASUREMENTS: Three separate measurements can be used as an indicator of NPP.

(1) **Vegetation Greenness:** The resources required to monitor chlorophyll content or greenness involve image acquisition and processing. Satellite data extends back to 1972 with the LANDSAT thematic mapper and LANDSAT multispectral scanner data sets. Satellite data having coarse spatial resolution (1.1 km) from the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) has been used to conduct long-term regional analyses of vegetative response to stressors (e.g., Asrar et al. 1985; Tucker et al. 1985; Becker and Choudhury 1988). Extensive ground truthing of remotely sensed measurements of vegetation are under way in the First International Satellite-Land Surface Climatology Program Field Experiment Program of the National Aeronautic and Space Administration (NASA). NASA plans to undertake a second such experimental program within the next several years.

(2) **Annual Wood Increment:** Measurement of relative woody growth increment requires approximately 0.5 h of technician time per plant. There is a spectral signature for lignin and cellulose (the constituents of wood); thus it may be possible to monitor annual changes in woody biomass remotely.

(3) **Ratio of Root Biomass to Shoot Biomass:** Examining root/shoot ratios in nature is labor intensive and depends greatly on the size of the plant and the precision desired; estimated labor costs are 1 day of technician time for each sample shrub.

INDEX PERIOD: To assess the potential NPP in seasonally active grassland, shrubland, and woodland systems, the sampling window for remote sensing should include the period of peak vegetation growth to facilitate repeatability among years. Growth increments in woody plants and annual standing biomass in ephemeral vegetation (e.g., grasslands) should be measured at the end of annual or seasonal periods of productivity.

VARIABILITY: The expected spatial variability of biomass measures within a resource sampling unit varies with habitat quality; the range can deviate >100% from the mean value. Under some conditions vegetative cover and productivity are quite uniform, for example, across flat valley bottoms. Because the entire resource sampling unit is being monitored, the expected spatial variability of remotely sensed data is inconsequential. The expected temporal variability of the biomass measures during the index period were not estimated.

PRIMARY PROBLEMS: The most significant problem is that the field measurements are all labor intensive. Additional research is needed to determine if spectral signatures other than that of chlorophyll can be used to determine specific details about the physiological or functional status of plants. Detectable changes in the quantity of other plant pigments should be useful in this regard.

In assessing the impact of some environmental change, it would be extremely useful to quantify a species' potential NPP by the availability of its limiting resources. This is a simplistic assumption, however, because in most cases plant growth is limited by multiple resources. In arid zones, for example, water is an important resource, but the growth rate of most plants inhabiting these areas also increases in response to N applications. Research to develop an improved understanding of the effect of resource limitations on NPP is therefore needed.

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E.2 INDICATOR: Riparian Extent

CATEGORY: Response/ Ecosystem Process Rates and Storage
Exposure and Habitat/ Landscape

STATUS: High-Priority Research

APPLICATION: This indicator is designed to monitor the areal extent of riparian habitat in arid lands both as a threatened resource class that directly relates to environmental values such as water quantity and quality, soil erosion, and aesthetics and as extent affects animal and plant populations. Riparian habitats in the West have been widely depleted and degraded (U.S. GAO 1988; Johnson and Simpson 1985). Because of their unique dependence on surface waters and their intense human utilization or manipulation, riparian systems are capable of reflecting the overall condition of surrounding ecological resources (Groeneveld and Griepentrog 1985).

INDEX PERIOD: Satellite data of late spring to early summer is best for monitoring the status and extent of riparian systems, because the riparian vegetation is in a full leaf-out condition, and a high sun angle reduces shadow effects in steep terrain.

MEASUREMENTS: Riparian zones associated with rivers, streams, and springs stand out clearly on remotely sensed data of grasslands, shrublands, and woodlands. The areal extent of riparian vegetation can be readily tracked by using Thematic Mapper (TM) satellite data (e.g., Groeneveld et al. 1985). This can be accomplished with aerial photography or airborne video data, in conjunction with a field survey program.

The estimated costs of remote-sensing-based measurements performed on a landscape sampling unit are the following: (1) TM or airborne data purchase (~$500), (2) computer time (~$500), and (3) analyst time (~$500). Thus the total cost per landscape sampling unit would be about $2000. The recommended interannual sampling frequency would be approximately five years.

VARIABILITY: TM data would provide full spatial coverage of each landscape sampling unit; therefore, considerations of spatial variability for parameters within a resource sampling unit are inconsequential. The expected temporal variability of riparian extent during the index period would produce a range that deviates <10% from the mean value.

PRIMARY PROBLEMS: The tracking of species composition changes cannot be performed in detail by using satellite data. Monitoring for these changes must be done by low-altitude remote sensing and field surveys.

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E.3 INDICATOR: Energy Balance

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: High-Priority Research

APPLICATION: The input of solar energy drives the interrelated biogeochemical cycles of carbon, oxygen, nitrogen, water, etc., in virtually all ecosystems. Solar energy impinging upon a site is dissipated through a mix of five primary flux processes or pathways: reflection, reradiation, conduction of sensible heat into the ground, sensible heating of the air, and evaporating water as latent heat in the air. The rates of several important biogeochemical cycles (e.g., H_2O, C, and O) are directly dependent upon or closely related to the particular mix of these dissipation processes occurring at any given time. Because these biogeochemical cycles are linked to energy dissipation processes in well-characterized ways, the rates of some biogeochemical processes, an indicator of ecosystem function, can be inferred from the relative rates of energy dissipation processes.

Sensible and Latent Heating of Air: A measure of particular importance is the Bowen ratio, the ratio of sensible heat flux to latent heat flux in air. This ratio in essence indicates the relative importance of the hydrologic cycle as an energy dissipater at the site of measurement. When vegetation is present, stomatal conductance and the resultant rate of plant transpiration are usually the factors controlling the Bowen ratio. Nowhere is this more true than in arid and semiarid environments (Jarvis and McNaughton 1986). Other factors which influence the Bowen ratio are leaf area and surface aerodynamic roughness.

It has been demonstrated that stomatal conductance is primarily and linearly related to the leaf photosynthetic rate, given constant relative humidity and CO_2 concentration (Wong et al. 1979, 1985). The conductance/photosynthesis relationship increases linearly with relative humidity and as an inverse function of the CO_2 concentration (Ball et al. 1986; Ball 1988). The photosynthetic rate, relative humidity, and the CO_2 concentration thus form a multiplicative index to which stomatal conductance responds linearly. The slope of the conductance response varies between species and particularly between C_3 (cool climate) and C_4 (warm climate) species.

The Bowen ratio, then, directly reflects the photosynthetic capacity of the area's vegetation and would change if the site's vegetation changed. Impacts on the vegetation by factors such as air toxics, which enter leaves and affect photosynthesis, would be expected to induce a decline in stomatal conductance and a decrease in water vapor and latent heat flux from vegetation. Such a change could be taken as an early warning sign to long-term vegetation change. Also, because the Bowen ratio reflects stomatal conductance and many pollutants must enter the stomata before they affect plant metabolism, this measure of stomatal conductance may indicate susceptibility of ecosystems to airborne pollutants. The plant-mediated flux of water vapor and accompanying latent heat into the atmosphere is one of the primary feedbacks that the vegetation has upon climate.

Reflection: Reflectance of the total solar spectrum (measured as surface albedo) can be a major route of solar energy dissipation. The albedo can range from near zero above heavy vegetation cover or above soils rich in organic matter to values as high as 0.7 in areas where a salt crust covers the soil. Particularly in arid and semiarid regions, loss of vegetation generally results in increased albedo. Thus with vegetation loss, incoming energy which might have been dissipated as latent or sensible heat in the lower atmosphere is reflected back through the atmosphere.

Soil Heating: Soil heat flux can be a major energy dissipation pathway, especially where vegetation is sparse and soil is dark or moist. On both a diurnal and annual basis, the net flux of energy to or from the soil will be near zero unless the climate is changing. Thus soil temperature measurements made at opposite points in either the diurnal cycle or the annual cycle give a good indication of the importance of soil heat flux to the energy balance of a site for the respective time scales, especially if soil heat capacity and thermal conductivity are determined. For example, Schmidlin et al. (1983) found that mean annual soil temperature of well-drained soils in Nevada can be estimated from as little as two readings taken on equally spaced months (e.g., January and July, February and August). They then correlated mean annual soil temperature with elevation and geographical parameters. These parameters would, of course, change and have to be recalibrated if the climate warmed or cooled. Soil temperature records would be valuable in tracking climatic change and can be used in conjunction with soil water measurements. These parameters provide a baseline against which future changes in soils may occur in response to climate change (e.g., soil C and N content; Post et al. 1982, 1985; Parton et al. 1987).

Solar Radiation: There is a paucity of high-quality measurements of solar radiation across North America. In part, this lack of data stems from problems in interpreting remote measurements of solar radiation, such as the deposition of dust, etc., on instrument lenses and the inability to differentiate types and altitude of clouds (which influence downwelling long-wave radiation). A well-executed, larger, long-term solar radiation sensor network would prove particularly valuable in testing the hypothesis that increased cloudiness tends to mitigate the influence of increasing "greenhouse gases" in the atmosphere.

Reradiation: Remote measurement of reradiation (i.e., terrestrial radiative flux) is probably not practical. Although durable, semiconductor-based thermopile sensors are available, their field of view is probably too small to capture the heterogeneity of radiative surfaces at a site. There are a number of approaches to estimating terrestrial radiative flux, including direct temperature measurement and application of the Stefan-Boltzman equation (Sellers et al. 1988).

In summary, regular and continuous monitoring of the surface energy balance parameters, particularly the Bowen ratio, constitutes an excellent means of assessing the functional state of the primary producers within an ecosystem. Linked with satellite measurements of plant canopy characteristics, the energy balance can be used to calibrate and validate inferences of the functional state of the vegetation. Continuity of measurements from simple automated stations can give critical temporal information at a frequency which is not practical for satellite-based measurements. Continuous solar radiation records could be a very significant data base, especially in addressing questions regarding climate change.

INDEX PERIOD: In general, data on energy balance in arid and semiarid ecosystems would be most valuable for the period when plants are metabolically active. Monitoring stations can be easily automated and should operate continuously; year-round solar radiation measurements might be especially valuable.

MEASUREMENTS: Measurements should emphasize an understanding of regional energy balance and its connection to remotely sensed data (Kittel and Schimel 1987; Running et al. 1989). Advanced Very High Resolution Radiometer satellite data would be used to measure surface albedo and temperature on an annual or seasonal basis. Thematic mapper and SPOT satellite data would provide more detailed spatial resolution of albedo and temperature changes on a less frequent basis.

Field measurements provide information about process-level ecosystem function which can not be directly measured with remote sensing techniques (e.g., Vukovich et al. 1987). Measurement of the Bowen ratio, for example, involves measurement of wind vectors, air temperature, and humidity at the base of the planetary boundary layer. A small station with appropriate pyranometers, thermocouples, humidity sensors, soil heat flux plates, and satellite-linked data retrieval would cost approximately $8000.

VARIABILITY: Spatial variation in energy balance parameters is largely a function of vegetation type and land use. Temporal variation is a function of available soil water within and among seasons. Assessment of regional variation in surface energy balance is currently under way in tallgrass prairies by the International Satellite Land Surface Climatology Program of the National Aeronautics and Space Administration, First Field Experiment (Sellers et al. 1988)

PRIMARY PROBLEMS: Research is needed to determine what remotely sensed canopy parameters should be used to drive regional level models of energy balance. Data on stomatal responses to photosynthesis, humidity, and CO_2 need to be extended to a wider variety of species than is currently available. These data would need to be placed in a framework which links particular stomatal characteristics to plants typical of particular ecosystem conditions (e.g., disturbance). Maintenance and calibration of sensors, especially pyranometers, would be an important concern.

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E.4 INDICATOR: Water Balance

CATEGORY: Response/ Ecosystem Process Rates

STATUS: High-Priority Research

APPLICATION: Water is a resource critical to arid ecosystems. As precipitation amounts decline, the variability of precipitation generally increases markedly; this variability has important consequences for evolution and adaptation of arid zone organisms and the functioning of arid ecosystems. Some organisms have evolved structural, functional, and life history attributes specialized for dealing with variability in water supply, while others have evolved traits which allow them to exploit relatively stable water sources. Two examples of organisms that require relatively stable water supplies are mesquite (*Prosopis* spp.), which uses primarily ground water, and riparian zone species, which can use a combination of surface water and ground water. Despite adaptation of their component species to restricted and variable water supplies, both decreases and increases in water supply can significantly affect the productivity and species composition of arid lands. Water balance affects productivity of animals ranging from soil microorganisms to vertebrates. Plants have a major impact on water supplies, not simply because they consume the resource, but equally importantly, they intercept precipitation and contribute to soil conditions favorable for percolation of water into the soil. Monitoring of water balance in arid regions can thus be used as a predictor of ecosystem productivity and as an indicator of disturbance. Also, transpiration is a significant portion of the hydrologic cycle because it represents one of the important feedbacks of the biosphere to the atmosphere and climatic system. Any water balance monitoring program must be closely linked to synoptic and local weather monitoring efforts. Particularly important as an indicator of changes in ecosystem function is a change (increasing or decreasing) in the variability of values for the three water-balance parameters discussed below.

Water Consumption by Vegetation: As was briefly discussed under "Energy Balance" (indicator E.3), water consumption by plants is closely tied to photosynthetic activity. This is true not only because stomata must be open for photosynthesis to occur, but also because stomatal conductance to water vapor and to CO_2 is apparently linearly related to the photosynthetic rate of a leaf (Wong et al. 1979, 1985; Ball et al. 1986). In monitoring the Bowen ratio (see indicator E.3), the latent and sensible heat fluxes are determined separately so that a value for water flux can be obtained from vegetation. Recent work by Carlson and Buffum (1989) suggests that it may be possible to track evapotranspiration on a regional scale by using a combination of satellite remote sensing data and data from the meteorological network. Atmospheric stressors which enter leaves and affect photosynthesis (e.g., air toxics) would be expected to induce a decline in stomatal conductance and a decrease in water vapor and latent heat flux from vegetation. Such a change could be taken as an early-warning sign of long-term damage to vegetation. Any decrease in stomatal conductance (reflected in a lower rate of water use) should render a plant less susceptible to damage from airborne toxics, which require direct access to the leaf mesophyll cells before damage can occur.

Measurement of the ratio of stable C isotopes ($^{13}C/^{12}C$) accumulated in leaves provides an integrated measure of the ratio of stomatal conductance to photosynthesis (Farquhar et al. 1982). Coupling stable C isotope abundance measurements with measurement of the H and O isotopes accumulated in leaf material appears promising as a direct integrator of the amount of water expended for each unit C gained and of the relative humidity of the air at the leaf surface. The interpretation of the H and O isotope abundances in leaves is less well established than that for C isotope abundances (White 1988). Both the H and O in ground water tend to be enriched in the respective heavier isotopes (^{2}H and ^{18}O) relative to surface water and the meteoric water line. By sampling relative abundance of these isotopes in water within a plant and in the alternate water sources, it is possible to determine the portion of water coming from the two sources.

Ground Water Depth and Use: As mentioned above, some highly productive arid ecosystems utilize relatively stable ground water sources. Fluctuations may either force plants into drought stress or flood the root zone. Plants which normally use stable water supplies are less likely to withstand water stress than plants which normally encounter fluctuations in water supply. Fluctuations may also affect salinity or trace element accumulation. Lowered ground water depth due to increased pumping, upstream impoundment, diversion, channelization, etc., could adversely affect such communities. In extreme cases, withdrawal of ground water has caused the ground to collapse or sink. In arid regions, ground water levels can stabilize, once near-equilibrium between use and inflow is achieved. Salts accumulate in soil above such a water table, which becomes an "inverted leaching" profile. Shifts in a water table could result in changes in this salt accumulation profile, thereby providing a record of past shifts, against which ongoing shifts can be gauged.

Monitoring of Stream Flows: Runoff patterns vary markedly with differences in vegetation type, species composition, and areal cover, as well as with soil physical properties that influence infiltration. The southern shrubland and grassland ecosystems in North America are prone to flash flooding, in part because of sparse vegetation, but more because they are near the source of energetic subtropical storms. In these areas, monitoring of flooding events would be important for documenting erosion and possibly shifts in vegetation. In areas where flow is less episodic, stream flow data properly coupled to synoptic and local weather data is a good integrator of vegetation and soil conditions. Accumulation of records of stream flow data would provide a good baseline against which purported hydrologic change can be gauged.

INDEX PERIOD: Most measurement systems would record in place continuously; for example, flow gauges in streams and floats in wells. Data might exist or be obtainable only during specific seasons, such as Bowen ratio and stream flow data collected during growing seasons or well records at time of peak and least ground water withdrawal.

MEASUREMENTS:

(1) **Ground Water Level Monitoring:** Depth records to ground water and water table behavior are needed. Some ground water data bases do exist (e.g., U.S. Geological Survey), but their extent and usefulness is not known at present. To reduce regional uncertainty, new wells may need to be installed in existing networks. Well installation cost varies but is approximately $80/m ($25/ft).

(2) **Vegetation Use of Ground Water Versus Surface Water:** Both H and O in ground water tend to be enriched in the respective heavier isotopes (^{2}H and ^{18}O) relative to surface water and the meteoric water line. By sampling the relative abundance of these isotopes in water within a plant and in the two alternate water sources, the contribution of water from each source can be determined.

(3) **Historical Fluctuations:** As wells are installed, exchangeable Ca, Mg, Na, and K are measured in soils above the water table. Graphic plots of exchangeable cation profiles as a function of height above water table would indicate previous positions of the water table. Based upon an additional $20 a sample for analyses, 15 samples a core (25-50-cm intervals), and 10 cores per unit, the total cost is $3000 for each resource sampling unit.

VARIABILITY: Ground water depths will vary within a resource sampling unit. Water use by vegetation is likely to be rather consistent (with ranges that deviate <10% from mean values) if the cover and slope exposure are uniform; however, this kind of uniformity in land surface is rarely found. Stream flow will be highly variable (with ranges that deviate <100% from mean values) across a resource sampling unit, depending largely on topography, precipitation event size, and localization, but also on vegetation cover type and density.

PRIMARY PROBLEMS: Establishing a network of wells for ground water measurements on remote sites would be expensive. H and O isotope methodology for plant-ground water and plant-atmosphere interactions needs more research. The use of these methods may be restricted to sites with stable ground water. They probably work less well in riparian zones, washes, or playas. Subsoil may be highly heterogeneous in texture and mineralogy, thereby increasing variability in analyses.

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E.5 INDICATOR: Soil Erosion

CATEGORY: Response/ Ecosystem Process Rates and Storage

STATUS: High-Priority Research

APPLICATION: Accelerated erosion is one of the primary indicators of desertification (FAO 1979) and is closely linked to vegetation loss and surface soil disturbances (Webb and Wilshire 1983). Structural characteristics of natural shrubland and grassland soils are extremely sensitive to disturbance. Structural degradation initially manifests itself by destruction of soil crusts (cf. indicator E.11, "Abundance and Species Composition of Lichens and Crytogamic Crusts") and changes (generally a decrease) in infiltration rates. The destruction of soil crusts and loss of vegetation in disturbed areas can result in increased wind erosion. Decreases in soil infiltration rates are associated with increased runoff, which accelerates sheet, rill, and gully erosion.

Water erosion consists of particle detachment (interrill or sheet erosion) followed by particle transport (rill and gully erosion). A landscape in nominal condition would be characterized by a naturally established drainage density, a standard ratio of interrill to rill area, and a stable erosion rate. Disturbance of native soil structural characteristics would result in an alteration of the interrill/rill ratio and an accelerated erosion rate. If continued, the drainage pattern for an impacted area becomes more dense and more linear in outline.

The rate of wind erosion is controlled by wind speed and physical properties of the soil. Shrubland soils are commonly protected from wind erosion by vegetation, which breaks the wind speed at ground level and holds soil in place with its roots. Soil crusts (including cryptogamic crusts) also serve to resist wind erosion. Areas which have lost vegetation and the protective soil crusts are subjected to wind erosion during episodes of strong winds. This indicator would track a series of parameters linked to or resulting from accelerated erosion, and would be applicable to all arid resource classes.

INDEX PERIOD: There is no optimal sampling window for this indicator. However, because of high seasonal variation, it must be sampled during the same season on repeat field visits.

MEASUREMENTS: (1) **Integration of Factors Linked to Water Erosion Susceptibility:** These factors include information on soil characteristics, slopes, rate and timing of annual precipitation, vegetation cover, and mechanical disturbance. These factors would be obtained from EMAP-Characterization (soil information and slopes), meteorological data, and the vegetation biomass and mechanical disturbance indicators (E.1 and E.17). The Food and Agriculture Organization (FAO 1979) provided an example of the development of the integration of factors to estimate water erosion susceptibility on a regional basis. The estimated cost is $500 a resource sampling unit.

(2) **Indicators of Accelerated Water Erosion:** The interrill/rill ratio, gully density, and alterations in drainage density and drainage pattern would be measured for appropriate soil/landform units by using low-altitude aerial photography or videography. The total cost of aerial data acquisition ($100) and analysis ($500) is $600 for each resource sampling unit.

(3) **Integration of Factors Linked to Wind Erosion:** Measures of vegetation cover, mechanical disturbance, and high wind events would be obtained by monitoring other indicators (E.1 and E.17) and meteorological data. These data would be integrated to identify areas at risk of accelerated erosion by wind. FAO (1979) provides an example of this style of integrated index for wind erosion. The estimated cost is $500 a resource sampling unit.

VARIABILITY: The expected temporal variability of erosion-related measurements derived from airborne data during the index period would produce a range that deviates 5-50% from the mean value. This variability is induced primarily by seasonal and diurnal alterations in illumination conditions and can be largely eliminated by acquiring data with standardized illumination conditions. Because the remote sensing data will census the entire resource sampling unit, the spatial variability of measurements is inconsequential.

PRIMARY PROBLEMS: Measurement procedures must be standardized. The integration of factors to obtain indices for wind and water erosion would require some effort but is achievable.

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E.6 INDICATOR: Charcoal Record

CATEGORY: Response/ Ecosystem Process Rate and Storage (Retrospective)

STATUS: High-Priority Research

APPLICATION: The purpose of charcoal analysis in a monitoring program is to identify areas where plant communities are or were undergoing stress. When plant communities are under stress, fire frequency increases. Healthy communities are characterized by lower fire frequency. Actually, the relationship is much more complex than this description, because although a community may be unhealthy, the fire starting agent (e.g., lightning or man) must also be present. Fires reflect stress factors such as beetle kill, drought succeeding periods of wet climate when fuels were accumulating but not being burned off, or the impact of fires on accumulated fuels after fire suppression policies. In addition, periods of forest clearance by humans can be identified by periods in pollen records when charcoal abundance increases.

By constructing a charcoal record, a natural or baseline fire frequency can be determined for any plant community from which to judge current trends in fire frequency. Charcoal frequency is used more as a regional indicator than is pollen production. Because we can identify the origin of certain pollen types (e.g., aquatic and littoral plant pollen) as local rather than regional, we can separate between local and regional signals. This cannot be done with charcoal. Therefore, charcoal becomes by default an indicator of regional fire rather than local fire. Although a locally occurring fire may temporarily mask the regional charcoal fire record, with great quantities of charcoal, the use of several collection localities within a resource sampling unit would net a good regional record, because local fires can be factored out of the record.

INDEX PERIOD: Collection in early winter after the fire season is best, because the fire activity during the previous fire season can be assessed.

MEASUREMENTS: Two types of measurements must be taken: (1) Charcoal abundance: As with pollen abundance the use of tracers in the sample, given a standard sample volume or collection area size, can be used to derive charcoal abundance. (2) Charcoal size: Changing size is monitored by direct measurement with an ocular micrometer. Both changing charcoal abundance and size can reflect both changing fire frequency and fuel type. Larger charcoal and more abundant charcoal is produced by pine forests than by sagebrush steppe. But when the environment remains the same, changing charcoal size and abundance reflect changing fire frequency and indirectly changing plant community health. Cost of charcoal analysis can be covered under the pollen analyses costs. As with pollen analysis, an interannual sampling frequency of the same frequency as is used for sampling fossil pollen cores would be adequate for revealing evidence of plant community stress or change.

VARIABILITY: The expected spatial variability of charcoal records within a resource sampling unit was not estimated. Because the charcoal records are temporally integrative measures, the variability during the index period is inconsequential.

PRIMARY PROBLEMS: As mentioned above, the primary problem would be a temporary masking of the regional charcoal record by local fires.

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E.7 INDICATOR: Species Composition and Ecotone Location of Vegetation

CATEGORY: Response/ Community Structure

STATUS: High-Priority Research

APPLICATION: Species composition and ecotone location are important integrators of environmental change in arid and semiarid regions. These parameters could (1) determine the effectiveness of land management practices, (2) detect the response of vegetation to man-made stressors, and (3) detect vegetation response to fluctuations or alterations in long-term climate patterns.

Vegetation patterns in the arid zones frequently have sharp boundaries between competing plant assemblages. These boundaries are known as ecotones. A prime example of a prominent ecotone is the boundary between sagebrush and pinyon-juniper woodlands in the Great Basin area covering Nevada and Utah. Another example is the distinct boundary separating annual grasslands from chaparral on the central California coast. The position of these ecotones is known to respond to changes in climatic regime. These ecotones can be readily located on Thematic Mapper (TM) satellite data. This capability offers a tool for detecting vegetation shifts in response to climatic change or changes in land-use practices or other agents.

Species composition responds to a large number of factors, including grazing pattern, changes in soil properties, fire, mechanical disturbances, erosion, water availability, and climatic fluctuations/alterations. The spatial and spectral resolutions of current satellite data are too coarse to adequately determine species composition in most sparsely vegetated arid landscapes. The measurement of species composition would require low-altitude aerial photography and field measurements. This indicator would be applicable to all arid resource classes.

INDEX PERIOD: The optimal sampling window would be during the growing season from late spring to early autumn, when most species are flowering.

MEASUREMENTS: Species composition and ecotone locations would be measured by using low-altitude aerial photography (<1 m resolution) and field measurements. Trained interpreters can quantify species composition and delineate ecotones from aerial photographs or airborne video data. Driscoll and Reppert (1968) provide a description of these techniques. Field measurements of species composition would be reported in two ways: (1) number of individuals per unit area (density) of a species, and (2) the areal cover of a species as a fraction of the total ground cover. Methods for conducting field measurements are available (U.S. BLM 1985). Estimated costs for the analysis of aerial photography is $1000 for each resource sampling unit. Estimated costs for field measurements of species composition is $300 a resource sampling unit; cost will vary with each type of vegetation community.

Although satellite imagery is not useful for making diagnostic identifications of species composition, it can be used to monitor ecotone movement. TM data would be used to delineate the ecotone of adjacent vegetation types. This can be performed by using the results of field and aerial photograph surveys to provide actual species compositions. Changes in ecotone location can then be monitored with repeated coverage by satellite sensors. Estimated cost is $500 per landscape sampling unit.

VARIABILITY: Estimates of species composition for annual plants are subject to wide seasonal variation; perennial plant measurements would be less variable. The expected spatial variability of species composition within a resource sampling unit would produce a range that deviates 5-10% from the mean value and would be different for each plant community.

PRIMARY PROBLEMS: The standardization of measurement practices would be the foremost problem encountered in the application of this indicator.

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E.8 INDICATOR: Dendrochronology: Trees and Shrubs

CATEGORY: Response/ Population (Retrospective)

STATUS: High-Priority Research

APPLICATION: Changes in growth-ring characteristics (e.g., annual ring width) over time can be calibrated with measures of plant productivity. For example, it would be feasible to reconstruct long-term (50 to several hundred years) changes of above ground biomass production in sagebrush or pinyon-juniper habitat types (Ferguson 1964). Dendrochronology can also be used to date when trees and shrubs germinate and die and when growth is affected by anthropogenic factors such as pollution and land management practices.

The purpose of using time series of growth ring widths sampled from woody plants growing on climatically stressed sites is to provide a proxy of past climatic variability, including seasonal and annual temperature, precipitation, drought, and stream discharge. The long reconstructions (from 500 years to several thousand years) provide a sound basis for obtaining more reliable estimates of central tendency, variability, and time series characteristics than the normally short period of instrumental data. The long reconstructions of past climate provided by tree and shrub rings can also be calibrated with other indicators of paleoenvironmental change sampled at reasonably high frequencies. For example, pollen records from locations with rapid deposition rates have the potential to be sampled at close intervals, so that each represents a brief period of time.

Although arid ecosystem research has focused on tree rings of conifers such as pinyon, the dendrochronological/ecological approach is potentially applicable to any woody shrub, including sagebrush, with definable annual growth layers.

INDEX PERIOD: Normally one ring a year is added, although in years of extremely favorable climate, a double growth flush may occur; in drought years a tree may not add a ring completely around its circumference. Radial increment cores can be obtained from trees and woody shrubs at any time of the year, but the complete growth ring for a given year will be present only after the end of the growing season. For example, in the Great Basin this occurs in early autumn.

MEASUREMENTS: Annual growth layers from radial cores are measured under microscopic magnification to the nearest 1 μm on a computer-compatible linear measurement apparatus. A large body of micromainframe software is available to analyze the resultant series of ring width measurements. Each time series of tree ring widths (representing one core) is standardized to a mean of 1 and relatively constant variance over time by fitting a growth function to account for the age trend. This allows the growth records from slower growing older trees and faster growing younger trees to be averaged into a mean value function. The older trees normally contain a stronger climatic signal than younger trees, whose growth often reflects the effects of competition for water, nutrients and sunlight, and canopy position. The mean value function represents tree growth for one species at one location (stand) over time. The annual growth record can normally be calibrated numerically with time series of climatic data during the years of common overlap. If a verifiable numerical relationship can be established for the period of instrumental climatic record, the equation can be applied to the lengthy tree ring series to reconstruct past climate. In many arid regions the potential exists to create climatic reconstructions for the past 500 to several thousand years. A concise record of climate may be essential in establishing the frequency of climatic events that can dramatically alter ecological systems.

VARIABILITY: The quantitative variability in ring-width index can closely correspond to macroclimatic variability, according to the sampling design employed. Growth of trees and shrubs sampled on sites where climate limits the physiological processes controlling growth can be highly correlated with climate (60-80% variance in growth attributable to climate). Because climate can limit growth simultaneously at many locations in a region, it is not unrealistic to expect 50-75% variance in common among chronologies within a resource sampling unit. Woody plants sampled on sites where climate is not the primary stressor will reflect the influence of other factors such as competition and microclimate and will have little correlation with regional climate or with one another. Because the dendrochronological records are temporally integrative measures, the variability during an index period is inconsequential.

PRIMARY PROBLEMS: Reconstructing climate from wood-ring series is normally not a problem in the West. One factor of prime importance is the availability of meteorological data to calibrate with the wood-ring series. Lower elevations generally have the greatest density of weather stations, whereas information from higher elevations is more sparse. Wood-ring series can be used to reconstruct climate at considerable distances from where the trees are sampled. One common misconception concerns the difference between ring counting to date annual growth layers and a dendrochronological approach involving a procedure referred to as cross-dating. Cross-dating establishes the exact calendrical date of every ring in every radial increment core, by an exacting comparison of the growth patterns among all specimens. Ring counting does not yield exact growth ring dates, because a ring may be locally absent along a radius, or there may be a double growth flush in one year. If a dendrochronological approach utilizing cross-dating is not employed, any environmental information present in the series may be lost.

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E.9 INDICATOR: Pollen Record

CATEGORY: Response/ Population (Retrospective)

STATUS: High-Priority Research

APPLICATION: Pollen analysis can be used to identify past changes in plant communities. Interannual comparisons of stress is reflected in a decrease in both pollen production and pollen size. Once stress is removed (e.g., increased precipitation) both pollen production and pollen size increase. Over several years, changing proportions of pollen types will reflect community response to changing stress conditions. Pollen obtained from pollen cores of intense sampling can be used to extend these observations back in time beyond the brief period of environmental monitoring that is reflected in historical records.

INDEX PERIOD: The collection of samples is best in the autumn after the late summer and early autumn bloom is completed. This way the annual pollen output can be fully characterized.

MEASUREMENTS: In general, measurements of pollen production, size, and changing proportions are best taken from samples obtained near the edge of a plant community, where plants are most stressed naturally. Samples taken from well within a plant community would be less sensitive. Three types of measurements must be taken: (1) Pollen abundance: Knowledge of the deposition rate through the use of tracers would reveal changing pollen production of both individual species and the community as a whole. (2) Pollen size: Through measurements using an ocular micrometer, the mean and standard deviation of the pollen grain size distribution would reveal annual changes. (3) Relative abundance of pollen types: Changing proportions would reveal the community response to stress factors. Some species respond to stress more quickly and reflect this in changed outputs in pollen; longer term changes in species distribution also affect pollen production. The estimated processing cost is $180 a sample; the collection of pollen cores adds about $50 a sample. A sampling frequency of one year is adequate for revealing evidence of stress or changes in the plant community.

VARIABILITY: The expected spatial variability of pollen records within a resource sampling unit were not estimated. Because the pollen records are temporally integrative measures, the variability during the index period is inconsequential.

PRIMARY PROBLEMS: The viability of this indicator is mainly constrained by logistics. To best implement such an indicator, hundreds of pollen collection localities would have to be located and traps prepared within each resource sampling unit. Collection would have to be completed by winter snowfall, but after bloom-time. A network of pollen traps would have to be placed along elevation gradients and be in areas where they would not be disturbed by vandals or human activities (e.g., plowing) that would resuspend pollen in the air.

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E.10 INDICATOR: Woodrat Midden Record

CATEGORY: Response/ Population (Retrospective)

STATUS: High-Priority Research

APPLICATION: The plant remains in strata of woodrat midden (den content) reveal long-term plant species community response to climatic and other environmental changes. Both plant species presence and health can be monitored on the scale of decades to tens of thousands of years. Community composition can be assessed by the presence or absence of plant species, and community health can be monitored by actual measurement of plant remains.

INDEX PERIOD: This indicator is insensitive to time of year and can be sampled at any time.

MEASUREMENTS: The sample interval depends upon the spacing of woodrat midden strata in time and the period included in each stratum. This can range from a woodrat midden sample with a decade to a century of material in each stratum and a century to many millenia between strata. The three primary measurements of woodrat midden data are as follows.

1. The materials of identified plant species are weighed separately to arrive at nonparametric quantifying of the midden materials.
2. The plant parts (e.g., seeds, fruits, leaves) of identified species are enumerated.
3. The size of fruits and seeds is recorded, because a change in size through time and among strata can reflect stress upon the plant community.

Both (1) and (2) above are dependent upon not only abundance in the plant community, but also upon the foraging behavior of the woodrat. The estimated cost from collection to analysis is about $1000 a sample.

VARIABILITY: Because woodrat midden strata are heterogeneous units, the spatial variability of plant species composition within a resource sampling unit can be considerable. Because the midden records are temporally integrative measures, the variability during the index period is inconsequential.

PRIMARY PROBLEMS: The primary problem is related to the influence of woodrat foraging behavior upon the material collected for the den and its placement in the den; therefore, data retrieved from a woodrat den cannot be quantified in the same way as dendrochronological, pollen, or charcoal data.

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E.11 INDICATOR: Abundance and Species Composition of Lichens and Cryptogamic Crusts

CATEGORY: Response/ Community Structure

STATUS: Research

APPLICATION: Lichens, fungal, and algal crusts are widespread on rock and soil surfaces of arid lands (Cameron 1969). In chaparral and woodlands, these organisms occur on the outer bark of plants, as well as on rocks and soils. They are important locally to preserving the stability of soils. Cryptogamic crusts stabilize soil by binding it with their thallial filaments, by armoring the surface, and by increasing surface roughness (Cameron and Blank 1966). These cryptogamic crusts are strong enough to protect underlying soil from raindrop impacts and wind erosion. Cryptogamic crusts are known to be quite sensitive to mechanical disturbance of soil surfaces (Wilshire 1983). Once they have been disrupted, the forces of wind and water are able accelerate erosion. Lichens in forests are known to be sensitive indicators of air pollution damage (Ferry et al. 1973; Anderson and Treshow 1984; see indicator D.11), and it may be possible to use cryptogamic crusts as an indicator of air pollution exposure in arid ecosystems. This indicator would be applicable to all arid resource classes.

INDEX PERIOD: The optimal sampling window would be during the growing season from late spring to early autumn.

MEASUREMENTS: The measurement of lichens and cryptogamic crusts requires field work. Techniques which may be amenable to the measurement of abundance and species composition for these organisms include permanent photo plots, species richness, and density and areal cover by species. Methods for these measurements are available (U.S. BLM 1985). Estimated cost of measurement is $200 a resource sampling unit.

VARIABILITY: These organisms expand during moist times and contract during dry times; therefore, the expected temporal variability of this indicator during the index period would produce a range that deviates 5-100% from the mean value. Spatial variability within a resource sampling unit would vary over a similar range.

PRIMARY PROBLEMS: Measurement of this indicator is labor intensive and requires a high degree of training to identify species and perform adequate sampling. The full value of this indicator for arid lands is not currently established.

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E.12 INDICATOR: Foliar Chemistry

CATEGORY: Exposure and Habitat/ Tissue Concentrations

STATUS: High-Priority Research

APPLICATION: Foliar analysis can be used as an indicator of elemental availability in soil or atmospheric deposition. The vector analysis described below can be used to determine if vegetation is experiencing increases in nutrient or toxin concentrations that are in turn causing either negative or positive growth effects. Through a combination of foliar concentration and content, a reliable estimate of probable growth response to changes in nutrient and toxin status can be obtained. This information can be combined with stressor indicator data to determine if external inputs of nutrients are causing changes in productivity of a given species over its natural range. In arid vegetation, foliar Si has been shown to be a good indicator of grazing pressure (Cid et al. 1989).

INDEX PERIOD: Sampling should occur during periods of peak stable biomass.

MEASUREMENTS: For dominant (by biomass) species on site, total tissue concentrations of N, P, K, Ca, Mg, Na, S, Fe, Mn, Zn, Cu, B, Ti, Al, Mo, Cl, Si, Ni, Pb (10 foliar samples per species per sampling unit) should be measured. Leaves should be washed (quickly) with mild nonphosphate detergent solution. Unwashed leaves could be included for comparison and to estimate dust accumulation on leaves (differences in Al, Si, and Ti, especially). Observations to be made include Mn/Mo ratio changes (which indicate soil pH changes: Increased ratio, greater acidity).

For vector analysis, both foliar concentration and weight per leaf of new foliage are required. Samples are taken and analyzed as described above. Litter fall sampling is not recommended as a substitute for live foliage samples because the translocation of nutrients prior to litter fall to relatively constant concentrations (e.g., Turner 1977) would greatly reduce the sensitivity of litter fall as an indicator of nutrient status and change.

Foliar concentrations and leaf weights are plotted on a generic nomograph (Weetman and Fournier 1982), which depicts potential responses of first-year needle weight and elemental concentration to elemental input. This method has proven successful in predicting growth responses to fertilization in balsam fir (Timmer and Stone 1978), jack pine (Timmer and Morrow 1984), lodgepole pine (Weetman and Fournier 1982), and loblolly pine (Johnson and Todd 1988). The predictions from these nomographs should provide an early indication of plant response to changes in nutrient or toxin availability from atmospheric deposition or various site disturbances. The cost would range from $50 to $150 a sample.

VARIABILITY: The expected spatial variability of foliar elements within a resource sampling unit would produce a range that deviate <20% from the mean value. Temporal variability during the index period was not estimated.

PRIMARY PROBLEMS: Concerns include the lack of baseline data on many species and of understanding optimum sampling time. The vector analysis has not been tested on several species and may not work well in nondeterminate species (e.g., species that initiate growth whenever conditions are favorable rather than during a specific season each year).

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E.13 INDICATOR: Physiochemical Soil Factors

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: High-Priority Research

APPLICATION: The application of this indicator to arid lands is similar to the "Soil Productivity Index" indicator described for forests (D.8), but it is somewhat more intensive, especially with respect to soil physical properties. Quantitative pits (Hamburg 1984) in conjunction with soil pedon descriptions would be made on each ground sampling plot on a one-time basis for the purpose of describing the soil type and obtaining data on soil bulk density and the proportion of gravel (the latter to be used in calculating soil elemental contents on an aerial [kg/ha] basis). The soil would be classified according to the U.S. Soil Conservation Service Great Group Level or to a finer degree (e.g., series), if possible.

Periodic measurements of soil chemical properties would be used to detect temporal changes in soils and to correlate such changes with measures of soil moisture, temperature, plant growth, nutrient use efficiency, and other indicators that may be relevant to soil change. This indicator provides a baseline against which future changes in soils may occur in response to long-term climate change (e.g., soil C and N content; Post et al. 1982, 1985). Soil salinity changes also would be identified in response to changes in ground water levels and surface water movement patterns. Plant species composition or lack of plants (see Indicator E.7, "Species Composition and Ecotone Location of Vegetation") would also reflect soil salinity status.

For grasslands, changes in climate or land use (e.g., cultivation) can strongly affect soil organic matter storage (Schimel et al. 1990). Soil organic carbon (SOC) levels represent the balance between net primary production and decomposition and are a sensitive indicator of ecosystem function and status (see also indicator C.1, "Sediment and Organic Matter Accretion"). Decreases in grassland SOC from increasing decomposition rates are a likely consequence of global warming; as a result, these systems would become a net source of CO_2 and provide feedbacks to the climate system (Schimel et al. 1990). SOC response in shrubland or woodland systems may not be as important or detectable as in grassland because soil organic matter levels are low, but SOC responses in ecotones between forest and woodland would be a critical indicator of the desertification processes that may occur as a result of climatic change.

INDEX PERIOD: An optimal sampling time does not exist. However, because of the high seasonal variation, soil chemistry must be measured during the same season on repeat field visits.

MEASUREMENTS: Quantitative pits are soil sampling units in which the exact volume, weight, and particle size distribution of soil are measured by horizon (Hamburg 1984). These parameters represent nutrient concentration data on an areal basis (e.g., kg/ha). A minimum of 10 quantitative pits would be measured initially at each resource sampling unit, and within each pit a pedon description would be obtained. Samples for determination of long-term change would be taken randomly from a permanently established grid (e.g., 10 samples taken randomly within a 20- x 20-m grid during each sampling period). All samples would be analyzed for total C (LECO), total N (Kjeldahl), soluble salts (Rhoades 1982), exchangeable cations (Al, K, Ca, Mg, Na, Zn, Cu, Mo), and cation exchange capacity (1 M NH_4Cl), extractable SO_4^{2-} (0.016 M NaH_2PO_4), extractable P (bicarbonate), and extractable B (Bingham 1982). Pedon samples would also be analyzed for total P, S, K, Ca, Mg, Na, Zn, Cu, and Mo. All samples would be archived for potential additional analyses.

Pedon analyses and determination of soil bulk density and gravel fraction would be conducted one time only; soil nutrients would be sampled at five-year intervals. Costs of collection and analyses for soils would be approximately $150-$200 a sample for periodic nutrient collections and $300-$350 a sample for the quantitative pit samples. With a sufficient number of quantitative pits, measurement error (standard errors) can be maintained at <20%. Pedon analyses, soil bulk density, and gravel fraction would be sampled one time only. Soil nutrients would be sampled quarterly to allow an examination of seasonal variations, which can be significant with respect to certain extractable nutrients (e.g., extractable P).

VARIABILITY: The expected temporal variability of soil chemistry and structure in surface soil samples during the index period would produce a range that deviates <50% from the mean values. The spatial variability within a resource sampling unit ranges between 20 and 80%, depending upon depth and sampling unit size.

PRIMARY PROBLEMS: The high spatial variability of soil chemistry would be the greatest problem to be encountered, especially with respect to soil physical properties. This would necessitate more replication than is typical of most soil sampling protocols. Laboratory techniques for trace metals requires skill and care.

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E.14 INDICATOR: Exotic Plants

CATEGORY: Exposure and Habitat/ Exotics-GEOs

STATUS: High-Priority Research

APPLICATION: A number of the introduced species in the western United States are widely regarded as indicators of degraded conditions, including the presence of cheat grass (*Bromus tectorum*), tamarisk (*Tamarix* sp.), and tumbleweed. These plants have proliferated widely during the past 200 to 300 years since their introduction because of their adaptation to thrive in disturbed habitats. The presence and abundance of exotic plants can be used as an indicator of the condition of arid lands and would be applicable to all sites.

INDEX PERIOD: The optimal sampling window would be late spring to early summer.

MEASUREMENT: Data required for this indicator would also be collected for the "Species Composition and Ecotone Location of Vegetation" indicator (E.5) by aerial photography and field surveys. The estimated cost is $100 a resource sampling unit.

VARIABILITY: Estimates of species composition for annual plants are subject to wide seasonal variation. Perennial plant measurements would be less variable. The expected spatial variability of field measurements of species composition within a resource sampling unit would produce a range that deviates 5-10% from the mean value. The expected temporal variability of species composition measures during the index period would produce a range that deviates 20% from the mean value.

PRIMARY PROBLEMS: No major problems are anticipated when this indicator is assessed.

BIBLIOGRAPHY:

Oosting, H.J. 1956. The Study of Plant Communities. W.H. Freeman and Co., San Francisco.

E.15 INDICATOR: Livestock Grazing

CATEGORY: Exposure and Habitat/ Exotics-GEOs

STATUS: High-Priority Research

APPLICATION: The majority of areas to be monitored by EMAP-Arid Lands is subjected to livestock grazing, on both public and private lands. Although grazing is restricted or prohibited at some federal land holdings (national parks and wilderness areas), these areas account for only a small fraction of the total land area under consideration. Cattle and sheep grazing in the western United States has produced major impacts on 40 to 80 million hectares (100 to 200 million acres) of federal land (U.S. GAO 1988). In addition to cattle and sheep, grazing by feral animals (wild horses and burros) must be considered. Grazing alters plant species composition and vegetation cover, impacts riparian systems, and can accelerate erosion (U.S. BLM 1978). This indicator would provide estimates of grazing intensity, and it is applicable to all arid resource classes.

INDEX PERIOD: A seasonal record of actual use is required to document in terms of "animal unit months" the time over which an area has been grazed.

MEASUREMENTS: A livestock grazing record should be acquired for each resource sampling unit. The U.S. BLM (1978) describes the methods for collecting actual-use data. Actual use data consists of livestock counts, the kind or class of livestock, and the period(s) of time the livestock actually grazed the sampling unit (e.g., animal unit month). Several sources of actual use data exist and include the following.

(1) **Livestock Operator Reports:** Operators of grazing enterprises can be asked to submit reports documenting actual livestock grazing use. The U.S. Bureau of Land Management (BLM) and U.S. Department of Agriculture-Forest Service (USDA-FS) commonly request these reports to assess actual use and to calculate billings for federal land use.

(2) **USDA-FS and BLM Counts:** These two land management agencies often conduct head counts when livestock are moved onto or off their respective grazing allotments.

(3) **Direct Counts:** Field counts, aerial counts, and counts derived from low-altitude aerial photography are performed on localized areas by both the BLM and USDA-FS. Similar counts should be performed by EMAP field and aerial crews at the sampling units. This is the only technique that provides data on actual grazing by wild horses and burros.

The actual use data records would have to be acquired and processed to produce seasonal estimates of actual use. The estimated cost to acquire and process actual use data for a resource sampling unit is $500 a season.

VARIABILITY: The expected spatial variability of direct counts within a resource sampling unit would produce a range that deviates up to 100% from the mean value; the large variability is expected because of the mobility of livestock within grazing units that include portions of sampling units. Because the measures integrate grazing intensity throughout the season, an estimate of temporal variability of direct counts during a season was not required.

PRIMARY PROBLEMS: The primary problems with estimating grazing intensity would be the development of reliable and sustainable sources of actual use data. EMAP crews would not be in the field often enough to produce an adequate record of actual use data; therefore, the reliability and coverage of the data record would have to be thoroughly reviewed and assessed.

REFERENCES:

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E.16 INDICATOR: Fire Regime

CATEGORY: Exposure and Habitat/ Habitat

STATUS: High-Priority Research

APPLICATION: Fire occurs as a natural phenomenon in shrubland, grassland, chaparral, and woodland ecosystems. Fire plays a crucial role in the availability of plant nutrients in arid and semiarid regions where the rate of litter decay is low. In chaparral, fire removes overly matured stands of plants, allowing the vegetation in the burnt zone to be rejuvenated. Since the early 1900s, fires have been suppressed throughout the West. Gradually, however, land managers have realized the valuable aspects of wildfires and are reintroducing fire as a management practice in the USDA Forest Service and U.S. Bureau of Land Management.

Although fire is now recognized as having beneficial ecological effects, the timing and frequency of fires must be regulated to protect property and to avoid detrimental ecological effects. If fire occurs too frequently or if burning is too intensive, environmental damage such as the loss of soil nutrients, acceleration of erosion, or proliferation of less desirable plant species such as cheat grass (*Bromus tectorum*) can occur. For most areas there is an optimal frequency pattern for fire (e.g., once every 8-12 years) and an optimal season for producing a manageable and beneficial fire.

Fire frequency would be tracked by using remotely sensed data and verified with selective field surveys. In addition, fire hazard maps would be produced to indicate areas most prone to burning. This indicator is applicable to all arid resource classes.

INDEX PERIOD: The optimal sampling period is the peak growing season from mid-summer to early autumn or when the incidence of fire is approaching zero.

MEASUREMENTS: The location and spatial dimension of recent burns would be determined by using Thematic Mapper (TM) satellite data. Burns retaining charcoal can be recognized by the unique spectral characteristics of charcoal: low reflectance in the visible and high reflectance in the TM bands at 1.65 and 2.22 μm. Burnt areas without the charcoal spectral signature would be identified by a combination of factors (Chuvieco and Congalton 1988; Tanaka et al. 1983), including (1) brighter reflectance than that of surrounding unburnt areas due the removal of litter and soil organic matter, (2) diagnostic shapes such as sharp boundaries, windblown stringers, and cleared firelines, and (3) a lower perennial vegetation cover inside recent burns or a higher annual vegetation cover than that of the surroundings. Burnt areas frequently remain visible to TM sensors for decades. Estimated cost of TM data analysis is $200 for each landscape sampling unit.

Fire hazard maps (Chuvieco and Congalton 1989) indicating the probability of burning would be prepared by using (1) species composition and fuel loading, (2) elevation, (3) slope, (4) aspect, and (5) proximity to roads, trails, or building. This data would be available from EMAP-Characterization and the "Species Composition and Ecotone Location of Vegetation" (indicator E.7). Estimated cost of constructing fire hazard maps is $200 for each landscape sampling unit.

VARIABILITY: The expected temporal variability during the index period for measurements of burn area derived from TM data would produce a range that deviates <30% from the mean value. The variability is induced primarily by systematic alterations in illumination conditions over the index period and can be largely eliminated by acquiring data with standardized illumination conditions. Because the entire resource sampling unit would be censused, the spatial variability of fire regime measures within a resource sampling unit is inconsequential.

PRIMARY PROBLEMS: Standardized measurement procedures must be developed.

REFERENCES:

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E.17 INDICATOR: Mechanical Disturbance of Soils and Vegetation

CATEGORY: Exposure and Habitat/ Habitat

STATUS: High-Priority Research

APPLICATION: Mechanical disturbance of soils and vegetation is closely linked to several of the primary processes involved in land degradation (Webb and Wilshire 1983), including loss of plant cover, fragmentation of habitat, acceleration of erosion, and introduction of exotic species. Mechanical disturbances can be caused by grazing animals (U.S. BLM 1978), off-road vehicles, road and site constructions, mining, and mineral or fuel exploration.

This indicator would track the development of mechanical disturbance through time by using airborne and satellite imagery. It is conceded that the mechanical disturbances induced by grazing or single passes by vehicles on an undisturbed landscape would not be detected by this approach. However, it would be possible to detect and identify the new roads and trails, plus mechanically disturbed areas, created by mining and mineral or fuel exploration. The indicator is applicable to all arid resource classes.

INDEX PERIOD: The optimal sampling window is generally the growing season, from late spring to early autumn, when activities causing disturbances are likely to occur.

MEASUREMENTS: Standard change detection procedures would be applied to Thematic Mapper (TM) satellite data and low-altitude aerial photography or videography. Mechanically disturbed areas would be recognized by their spatial and spectral signatures; for example, they (1) are brighter than their surroundings, (2) have low to negligible vegetation cover, (3) have sharp boundaries, and (4) are frequently linear in shape. The identification and mapping can be accomplished by using the visual approach of photo interpretation. Automated approaches may accelerate this procedure and reduce costs. Estimated cost is $400 for each landscape sampling unit.

VARIABILITY: The expected temporal variability for measurements derived from remotely sensed data during the index period would produce a range that deviates 5-30% from the mean value. The variability is due primarily to the loss of details in heavily shadowed areas of steep terrain; variation in shadowing is induced by systematic alterations in illumination conditions both seasonally and diurnally. The high sun angles of mid-summer are best for reducing the obscuration of details in shadowed areas. Because the entire resource sampling unit would be monitored by remote sensing, the spatial variability of this indicator is inconsequential.

PRIMARY PROBLEMS: This indicator would not measure mechanical impacts due to grazing or single vehicle traverses on the landscape.

REFERENCES:

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Webb, R.H., and H.G. Wilshire, eds. 1983. Environmental Effects of Off-Road Vehicles: Impacts and Management in Arid Regions. Springer-Verlag, New York.

E.18 INDICATOR: Chemical Contaminants in Wood

CATEGORY: Exposure and Habitat/ Ambient Concentrations (Retrospective)

STATUS: Research

APPLICATION: Trees and woody shrubs may have recognizable annual growth layers that can be exactly dated to the year in which they were formed (see indicator E.8, "Dendochronology: Trees and Shrubs"). Samples of wood representing individual years, or intervals of years such as 5 years or decades, can be analyzed by various physical-chemical techniques to determine elemental concentrations with potential environmental exposure/dose information. For example, changes in elemental concentrations may be related to anthropogenic impacts such as air pollution. By constructing a contaminant record, a natural or baseline contaminant dose can be determined for any plant community from which to judge current or future trends in exposure. This indicator is applicable to shrubland and woodland resource classes.

INDEX PERIOD: An optimal sampling window during the year is based only on logistical constraints.

MEASUREMENTS: (1) Sampling procedure: usually two cores a tree, obtained from 30-60 trees of a particular species at a given location. (2) After radial cores are mounted and surfaced so that growth increments can be discerned, each core is cross-dated. The cross-dating procedure assigns each ring in each specimen to the exact calendar year in which it was formed. This is different from simple ring counting, which does not result in an exact chronological placement. (3) After each specimen is dated, wood samples associated with each time increment are removed (e.g., 5 years, decade). (4) The wood can then be subjected to various types of physiochemical analyses. The most common are inductively coupled plasma (ICP) optical emission spectroscopy and neutron activation analysis (NAA). ICP analysis typically yields information on the following elements: Ag, Al, As, B, Ba, Be, Bi, Ca, Cd, Co, Cr, Vu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Se, Si, Sn, Sr, Ti, Tl, V, and Zn. NAA can be used to obtain concentrations of elements such as As, Au, Ca, K, Mo, Na, Ba, Fe, Hg, Sr, and Zn.

VARIABILITY: The expected spatial and temporal variabilities within a resource sampling unit and during an index period would produce ranges that deviate 50-100% from their respective mean values.

PRIMARY PROBLEMS: It is difficult to determine and separate trends for anatomical distribution of elemental concentrations that are caused by changes in the environment from those for concentrations due to the normal physiological processes of a tree.

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APPENDIX F: INDICATOR FACT SHEETS FOR AGROECOSYSTEMS

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F.1 INDICATOR: Nutrient Budgets

CATEGORY: Response/ Ecosystem Process Rates & Storage
Exposure and Habitat/ Ambient Concentrations

STATUS: High-Priority Research

APPLICATION: The cyclic processing of chemical elements within an ecosystem is fundamental to the maintenance of its components. Organisms depend on the constant availability of some 20 elements which are required for all life processes. The effects of contaminants on nutrient availability ultimately translate into effects on many other aspects of ecosystem structure and function (Mittelman et al. 1987).

Nutrient concentrations in soil, and those in living organisms, and nutrient leaching from soil can be determined for an ecosystem; and major changes in these can provide an early warning of structural changes. The most frequent limiting factor for primary productivity, aside from water, is available (i.e., mineralized) N. Most soil N, however, is present in organic forms that cannot be assimilated by plants (Follett et al. 1981). A measure of mineralizable N would be useful for assessing the capacity of a soil to retain and supply N in a timely fashion; this capacity is related to soil and ecosystem quality. Such a measure would also be useful as an indicator of N export from the ecosystem because a portion of N is lost as gas during the mineralization process. The amount of N that would be mineralized is difficult to predict, however, because mineralization depends on numerous environmental factors.

Elemental ratios are another important metric of nutrient budgets, because these reflect nutrient storage in plants. Typical C:N ratios, for example, are known for corn stalks, small grain straw, clover, and alfalfa. Repeated variations from these typical ratios over time may be used to signal a change in ecosystem process rates. Similarly, elemental ratios that compare soil and plant tissues may be used to signal a similar stress response. If the elements appear to be plentiful in the soil but are not found in plant tissues, some stressor may be impeding assimilation. Other nutrient (e.g., P and K) budgets among the various ecosystem compartments (e.g., soil and plants) could also be used as early-warning indicators of ecological resource condition.

INDEX PERIOD: Soils should be sampled before agricultural fertilization in the spring or autumn. Spring sampling is recommended for estimating export of gaseous NO_x because microbial activity is greatest during the spring flush of growth. Vegetation could be sampled once or twice at the end of the growing season prior to harvest. Because mosses and lichens bioaccumulate contaminants continuously, their sampling window would be more flexible.

MEASUREMENTS: Traditionally, potentially mineralizable N has been estimated from mineral N accumulation during a 2- to 4-week incubation of soil samples; however, a chemical test called Electroultra Filtration includes an incubation time of <1 h. Data analysis for mineralizable N determination for each sample, therefore, requires either expensive equipment ($20K) and high cost ($30) and only one day, or less expensive equipment ($2K) and lower cost ($3) and more than two weeks (for incubation and analyses).

Elemental ratios on a national scale would be most efficiently examined either at state agricultural experiment stations or through local extension agents who would be more familiar with typical ratios for local crops and local soils and with typical nutrient deficiencies for the region. The experiment stations would be able to quickly identify the most appropriate ratios for any given region. A particular ratio that can be applied universally probably will not exist because of the high degree of variation in soil types, climatic effects, ratios in different species, etc. Examples of elemental ratios that could be examined include N:B, N:Ca, and C:N. Laboratory analysis for determining ratios would be inexpensive with mass spectrometry.

Concentrations of N, P, and K compounds would be determined in each ecosystem compartment, that is, soil, roots and foliage. Measuring soil leachate would provide a well-tested, sensitive method of monitoring changes in nutrient cycling because it reflects the rate that nutrients leave the system. Changes in the leaching rate can reflect the breakdown in nutrient-cycling processes. Leachate studies can detect small changes in nutrient content that are not measurable by other methods (Mittelman et al. 1987). Generally, in situ soil leaching analyses are performed with lysimeters.

Plant and soil sample collection would be labor intensive, involving a technician for 4 h and a scientist for 2 h at each resource sampling unit. Sample collection would be even more labor intensive for ratio determinations, requiring that soil and plant samples be taken from the same area. Analysis for metals by inductively coupled plasma would cost about $50-$75 per sample.

VARIABILITY: The spatial variability of soil nutrients is generally high, particularly on intensely managed landscapes such as agricultural land. The soil type would partially determine a soil's ability to provide or retain nutrients; soil experiencing different erosion rates would also affect its nutrient exchange capacity. Several soil types would often occur within a resource sampling unit, with varying degrees of erosion among those types. Variability among nutrients in plants would depend somewhat on the variability in the associated soils. The expected spatial variability of gaseous export within a resource sampling unit has not been determined. The expected temporal variability of each nutrient-cycling parameter during the respective index period is not available.

PRIMARY PROBLEMS: Once expected nutrient ratios are established for each region, no major problems are anticipated in the application of this indicator.

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Mittelman, A., J. Settel, K. Plourd, R.S. Fulton, III, G. Sun, S. Chaube, and P. Sheehan. 1987. Ecological endpoint selection criteria. Draft report prepared under Contract No. 68-02-4199 for the U.S. Environmental Protection Agency, Office of Research and Development, Exposure Assessment Group. Technical Resources, Inc., Rockville, MD.

F.2 INDICATOR: Soil Erosion

CATEGORY: Response/ Ecosystem Process Rates & Storage

STATUS: High-Priority Research

APPLICATION: Erosion of soil by water and wind is a natural process that is accelerated by human manipulation of the soil to optimize crop production. More than one fourth of the nation's 167 million hectares of cropland (413 million acres) is eroding at a rate that lowers soil productivity. Productivity of the land is reduced as the more productive topsoil is lost and part of the lower, less fertile layers are incorporated into the plow layer. As soil productivity decreases, additional fertilizer is often needed to maintain crop production. Excessive soil removal by erosion changes the water-holding characteristics of the soil or reduces the depth of the root zone. The decrease in plant-available soil water capacity is the major effect of erosion on crop productivity.

If the slope of the crop or pastureland is more than 2%, erosion by water is a hazard. Threats from this hazard can be reduced by maintaining protective plant cover, which also serves to increase infiltration, improve soil tilth, and provide nitrogen for subsequent plant growth. The removal or loss of plant cover due to poor management or stressful environmental conditions (e.g., drought, long-term climate change) can result in wind and water erosion and degradation of the ecosystem.

Erosion on farm lands allows sediments and chemicals to enter aquatic systems at higher rates. Controlling erosion minimizes the pollution of streams by sediment and improves the suitability of water for municipal use, recreation, and fish and other animals. Erosion and its associated nonpoint source pollution of aquatic systems are of interest to regulatory and most land management agencies.

Quantifying soil erosion provides a good indicator of the condition of our Nation's farmland. Long-term trends of soil loss can be evaluated in the proportion of soils that are subnominal according to their classification by the U.S. Soil Conservation Service (SCS). More than 601 million hectares (1,484,000,000 acres) had been mapped and were included in published soil surveys for the U.S. and Caribbean territories as of September 1987 (USDA 1983).

Soil surveys provide an erodibility factor (K) and a soil-loss tolerance factor (T) for each soil. K is the soil's susceptibility to erosion by water; T is the maximum rate of soil erosion from rain, wind, or environmental quality that can occur without reducing crop production. The soil-loss tolerance factor (T) is expressed as tons of annual soil loss per acre. Actual soil erosion (Tc) can be calculated from the universal soil loss equation (USLE) and a wind erosion equation (USDA 1983). These equations use the erodibility and index of a soil and related management, cropping, and environmental factors for the site to determine the annual erosion rates. The calculated erosion rates (Tc) can be compared to the acceptable soil-loss tolerance factors from the published SCS soil surveys. In addition to calculations, remote sensing and photographic interpretation could be used to determine the number of larger rills and gullies formed due to erosion. This type of assessment helps to complete the picture in assessing an erosion index indicator because the USLE does not account for large-scale gully erosion.

INDEX PERIOD: The best time for field sampling would be in late summer after cropping. The best time to count gullies would be in the spring prior to leafout.

MEASUREMENTS: Data can be collected by remote sensing and field visits. Soil loss values would be calculated from soil texture and slope length of fields (from soil surveys), land use and/or cropping data (remotely sensed or from the SCS National Resources Inventory), and sediment delivery ratios and rainfall data (from National Weather Service). Much of this data is already available and has been used for other data (from National Weather Service). Much of this data is already available and has been used for other purposes, but can be adapted. The recommended interannual sampling frequency is every year.

VARIABILITY: The spatial variability of soil erosion would depend mostly on the variations in slopes and soil types. The expected spatial and temporal variabilities of soil erosion within a resource sampling unit and during the index period, respectively, were not estimated.

PRIMARY PROBLEMS: No major problems are anticipated in the application of this indicator.

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F.3 INDICATOR: Microbial Biomass in Soils

CATEGORY: Response/ Populations

STATUS: High-Priority Research

APPLICATION: Soil microorganisms play an important role in the retention and release of nutrients and energy in agricultural soils. The role of soil microbes in soil energy and nutrient relationships was reviewed by Paul and Voroney (1980). Nutrient and energy fluxes influence the biological and chemical activity of an ecosystem and are sensitive to structural changes in that system.

Soil microbial biomass is the living part of the soil organic matter, excluding plant roots and soil animals larger than about 5000 μm^3 (Jenkinson and Ladd 1981). Although composed of a variety of different organisms, such as bacteria, actinomycetes, fungi, and microfauna, soil microbial biomass is usually treated as an undifferentiated whole. The treatment of this soil component as a single compartment is useful and integrative in providing a quantitative indicator of the flux of energy and material through the soil compartment of the ecosystem. Soil samples collected at a resource sampling unit can be partitioned to permit measurements that will contribute to other indicators, such as metrics of the index of soil integrity and the soils component of potential nematode stress (see indicator F.8, "Agricultural Pest Density").

INDEX PERIOD: Soil samples can be collected at any time of the year; however, collection of samples when crop plants are actively growing would increase the certainty of obtaining the maximum soil microbial biomass.

MEASUREMENTS: Soil microbial biomass will be estimated by a chemical technique that measures the flush of decomposition of soil biomass caused by fumigation with chloroform ($CHCl_3$). Soil organisms subjected to $CHCl_3$ vapors have their cell membranes destroyed by the vapor. This allows cell contents to leak into the soil, where it can subsequently be degraded by living microorganisms. The flush of decomposition is defined as the amount of CO_2 evolved by a fumigated soil over a given time less the amount of CO_2 evolved by the same amount of untreated soil in the same time (Jenkinson and Ladd 1981; Paul and Clark 1989). Although the amount of C that is evolved varies for fungi and bacteria, an average of 41-45% of fungal and bacterial C is evolved as CO_2.

Five assumptions are made in calculating biomass from the flush of CO_2 evolved by a soil that has been fumigated and then incubated (Jenkinson 1976):

1. The C in dead organisms is mineralized more rapidly than in living organisms (i.e., the protected C in a living cell becomes available to other organisms after cell death.)
2. Fumigation kills all soil microbes.
3. The biomass of organisms dying in unfumigated soil during incubation is negligible compared with that in fumigated soil.
4. The fraction of biomass C from dead organisms mineralized over a given time period does not differ in different soils.
5. Fumigation has no effect on the soil other than the killing of soil microbes.

The procedures for estimating microbial biomass from the CO_2 flush after soil fumigation were established and refined in a series of papers (Jenkinson 1976; Jenkinson and Powlson 1976a, b; Powlson and Jenkinson 1976; Jenkinson et al. 1979) and summarized by Parkinson and Paul (1982). The developed protocol, however, requires a 10-day incubation period before CO_2 evolution is measured. This incubation period makes the procedure resource intensive.

A modified procedure proposed and evaluated by Vance et al. (1987) reduces the post-fumigation incubation period, which makes the assay less resource intensive. Two composite samples would be taken for each resource sampling unit, each consisting of 10 soil cores that are 5 cm wide and 20 cm deep. After selecting an arbitrary starting point along one edge of a sample unit, soil cores would be collected along a zigzag pattern every 10-20 paces. Soil would be well mixed and stored at 5°C. Before biological analysis, soils would be sieved (<6.35 mm) and incubated at approximately 40% water-holding capacity at 25°C for 10 days.

The $CHCl_3$ extraction technique (Vance et al. 1987) has been tested on a limited number of soils, and its validity should be established on a wider range of soils. It is simpler than direct microscopy for the determination of soil microbial biomass (Paul and Clark 1989) and avoids systematic errors that are introduced when biomass is calculated on the basis of biovolume from the shrinkage of microorganisms with drying (Jenkinson and Ladd 1981). The $CHCl_3$ technique does not require standardization on each soil type like that required for the calculation of biomass C by adenosine 5′-triphosphate (ATP) extraction (Jenkinson and Ladd 1981). In addition, the ATP extraction technique is most successful for characterizing soils in which the microbial population is in a resting state at excess or constant phosphorus levels (Paul and Clark 1989), whereas the $CHCl_3$ extraction technique can be used at any time.

Collection of soil for two composite samples from each resource sampling unit would require 0.5-0.7 h. The estimated cost of analysis is $25 per sample.

VARIABILITY: Variation among samples from a resource sampling unit should be reduced by compositing of samples. The coefficient of variation (CV) for four soils with three replicate samples assayed per soil ranged from 11.5 to 15.8%, with a mean CV of 13.6% (Vance et al. 1987). The expected temporal variability throughout the year was not estimated.

PRIMARY PROBLEMS: Establishment of seasonal and regional standards for evaluating soil microbial biomass would require considerable effort and extensive knowledge of soil type, crop history, and management inputs. Extensive temporal variation in soil microbial biomass within a resource sampling unit may complicate establishment of a subnominal threshold value.

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F.4 INDICATOR: Land Use/ Extent of Noncrop Vegetation

CATEGORY: Response/ Ecosystem Process Rates and Storage
Exposure and Habitat/ Habitat

STATUS: High-Priority Research

APPLICATION: The monitoring of land use would indicate status and trends in resource condition, crop preferences, and grower perceptions concerning market opportunities and profitability. A shift in the ratio of ancillary area to cultivated area would indicate alternation of perceptions with regard to set-aside and soil conservation practices. Land use would be evaluated in relation to other indicators, such as soil erosion (F.2), soil productivity index (F.11), agricultural chemical use, and socioeconomic indicators. The areal extent and spatial relations of areas of noncrop vegetation in agroecosystems would be a habitat indicator that affects native animal diversity.

INDEX PERIOD: Land use can be determined any time when crops are growing in the field or when growers have made decisions concerning crops to be planted for the growing season; spring or summer would be preferable.

MEASUREMENTS: Land use within a landscape sampling unit would be assessed initially by EMAP-Characterization from remote sensing according to a classification scheme based primarily on the Anderson classification scheme (Zev and Lieberman 1984). Subsequently, land use within a resource sampling unit would be assessed by enumerators during field visits in cooperation with owners or operators. Specific items of interest are areas (1) under cultivation (rented, leased, or owned), by crop; (2) in permanent pasture, set-aside programs, or in fallow; (3) in use for feeder lots or confined animal operations; (4) in ponds for irrigation or waste containment; (5) in border area (e.g., woodlot, hedge row); (6) devoted to grass waterways; and (7) devoted to buildings, driveways, and paved areas. Information concerning grower rationale for selecting specific crops would aid in the interpretation of land-use information, although such information may be subjective.

Grower interviews would last 0.5-1.0 h for each resource sampling unit. Some errors in estimation may occur because of grower responses.

VARIABILITY: Because land use within a sampling unit is a census measure, the spatial variability of land use within a resource sampling unit is inconsequential. The expected temporal variability of land use during the index period is minimal.

PRIMARY PROBLEMS: Reliable identification of actual crop species present is not possible from remotely sensed data obtained from the thematic mapper (LANDSAT-V). Grower interviews and site visits or current, leaf-on aerial photography at 1:24,000 would thus be essential.

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F.5 INDICATOR: Crop Yield

CATEGORY: Response/ Populations

STATUS: High-Priority Research

APPLICATION: The principal function of an agroecosystem is the production of food and fiber for human benefit. For crops, agricultural production is quantitatively measured in yield that results in economic gain. Crop yield must be incorporated as a response indicator to assess the status and trends of agroecosystem condition. Yield integrates the action of a large array of biotic and abiotic factors experienced by the crop during the growing season, such as soil factors (e.g., type, moisture, nutrients), climatic variables (e.g., temperature, light, relative humidity, precipitation, wind), management practices (e.g., agricultural chemical applications, tillage, irrigation, crop cultivars, planting date and density), pests (e.g., insects), diseases, socioeconomic conditions (e.g., government policies, markets), and pollutants (e.g., ozone, sulfur dioxide, heavy metals). Crop yield is normally expressed as biomass per unit area.

The use of crop yield data to help determine the status and trends of agroecosystem condition must be qualified, because crop growth and subsequent yields depend on a number of external factors (e.g., national and international markets, management practices). Crop yield, however, is one of the best known measures of biological and chemical function in agroecosystems, and it has measurable responses to both natural (U.S. EPA 1978; Lowrance et al. 1984) and anthropogenic stressors (Benson et al. 1982; Treshow 1984; U.S. EPA 1978, 1986; Heck et al. 1988). Because many agricultural areas are highly managed and on-farm decisions are driven largely by socioeconomic factors, attributing changes in crop yield directly to increases or decreases in stressor frequency or intensity may be inappropriate. For example, farmers respond to observed reductions in crop vigor or yield by adjusting management strategies to minimize the effect. These management strategies might include changes in irrigation, agricultural chemical applications, or crop type/variety. The consequence of these changes is that the ecosystems remain highly productive, at least over the short term, and any decrease in yields due to stressors is postponed by management strategies.

INDEX PERIOD: Field sampling would occur at the end of the growing season.

MEASUREMENTS: If the U.S. Department of Agriculture's National Agricultural Statistical Service (NASS) area sampling frame were used to select resource sampling units, the cost would be minimal in comparison to constructing an EMAP frame. Most of the cost would be in retrieving, manipulating, and analyzing the NASS data. Yield data for crops not currently monitored by NASS would cost approximately $500-$1000 per resource sampling unit for NASS labor. Crop yield could be measured as biomass of marketable product harvested, as a production efficiency index (see also indicator D.1, "Tree Growth Efficiency"), or in relation to specific inputs such as fertilizer applied. All measurements would be conducted for crops annually.

VARIABILITY: A number of factors, discussed above, influence variability in crop yield. Objective measurement surveys of yield would produce relatively little spatial variability (coefficient of variation <20%) if cultivars, management practices, and soil were identical throughout the resource sampling unit. Because crop yield integrates growth over the entire period of productivity, the expected temporal variability during the index period is inconsequential.

PRIMARY PROBLEMS: Development of a yield index such as net primary productivity (biomass produced from each unit land area) and production efficiency (yield in relation to fertilizer/energy input) will be necessary to compare yield among different agronomic crops. Also, the threshold value for subnominal yield may depend on region.

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F.6 INDICATOR: Livestock Production

CATEGORY: Response/ Populations

STATUS: High-Priority Research

APPLICATION: The productivity of livestock operations, like crop productivity, is an environmental value for agroecosystems. As with other aspects of agriculture, the definition of a "healthy" livestock system is difficult to formulate. Traditional measurements of these systems are economic, that is, measured in terms of profits. Livestock operations, like crop production, are highly managed with the goal of maximum yield with minimum input. The operator provides a certain amount of food, water, and labor and expects a high livestock production. A certain amount of waste is produced and exported to other ecosystems via air and water media.

Livestock operations suggest two useful indicators, productivity and waste export; only the former is addressed in this discussion. Productivity is an economic barometer which quantifies livestock yield. Use of existing measures of productivity assumes that a productive system is a healthy one; although in the short term that is true economically, it may not be true when ecological costs are included. A highly productive operation with its waste exports may not be an ecologically healthy system.

Productivity is controlled by both economic and production criteria. Production factors include shelter, feed quality (nutrition), and genetic advances. One way to determine the effects of production criteria on productivity would be to define an ideal environment that resulted in maximum productivity. Research has been accomplished to optimize housing, reproduction, and nutrition independently. If the combination of these optima are linearly additive, it might be possible to define an optimal environment. It would then be possible to compare the deviations between productivity measurements from livestock operations and the maximum potential productivity for use as a response indicator of growth efficiency.

INDEX PERIOD: The sampling window is flexible, but for logistical efficiency should be handled as part of a summer enumerative survey questionnaire, such as that conducted by the National Agricultural Statistical Service of the U.S. Department of Agriculture (USDA).

MEASUREMENTS: Because productivity measurements differ with livestock type, no universal indicator of productivity could be applied across all livestock operations. For example, the days to reach 105 kg (230 lb) is a common measurement for swine operations (Mayrose et al. 1985) but would be meaningless for a poultry producer, who would be more interested in eggs produced or live weight at slaughter (Bull 1989). Reproductive and growth rate statistics for various livestock are also used and available (USDA 1989).

Growth rate and live weight at slaughter are accepted indexes of productivity for broilers. Rate of lay serves as the measure for egg-producing poultry. These statistics are available from the USDA (1989) on at least a state basis. It would be useful to form a production:input ratio as an indicator of animal growth efficiency. There are several commonly accepted measures of swine productivity. They include live weight at slaughter, number of days to reach 105 kg (230 lb), feed efficiency, breeding efficiency, and pigs per litter (Mayrose et al. 1985).

Data will be available from grower interviews and should be part of a regular enumerative survey. This part of a questionnaire should require <1.0 h.

VARIABILITY: Because livestock production, like crop yield, integrates growth over the entire period of productivity, the expected temporal variability of livestock production during the index period is inconsequential. Because this indicator would be censusing the entire resource sampling unit, the spatial variability within a resource sampling unit is also inconsequential.

PRIMARY PROBLEMS: Possible problems are currently under evaluation. Integration of socioeconomic programs into the indicator interpretation may be difficult.

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F.7 INDICATOR: Visual Symptoms of Foliar Damage: Crops

CATEGORY: Response/ Pathology
Exposure and Habitat/ Pathogens

STATUS: High-Priority Research

APPLICATION: Plants tolerate and adapt to most natural stresses caused primarily by variations in weather without being visibly damaged or deformed. Foliar symptoms and deformation (other than diseases and insect pests) are associated with abiotic stresses including pollutants, nutrient imbalance, or weather extremes; this response indicator relates to the environmental value of productivity.

Although various foliage symptoms (e.g., chlorosis and nerosis) may be caused by a variety of stresses, extension agents routinely use specific symptoms to diagnose plant problems. Trained observers can often identify specific stressors from the pattern of damage/deformation/chlorosis (Treshow 1984). Acute symptoms from air pollutants are readily diagnosed on selected indicator plants: SO_2 -ragweed, bachelor button (cv. Jubilee Gem), downy brore grass, alfalfa, *Ruellia caroliniana*; O_3 - milkweed, potato (cv. Norland), soybean, tobacco; and F - gladiolus, apricot (cv. Royal or Chinese).

For nonleafy crops where foliar symptoms do not affect crop productivity directly, it may be possible to relate the symptoms (in this case an exposure indicator) to a response indicator such as crop yield (F.5), which does reflect productivity. For some disease and insect problems, there are models that relate pest densities to yield effects (Campbell and Madden 1990); these would require calibration. Foliar symptoms are of greatest value in revealing acute exposures to specific stressors and thus are not the most sensitive indicator to reveal chronic pollutant exposures.

INDEX PERIOD: The sampling window is the season of vegetative growth (May to September); the optimal time of data collection depends on the objective. A monthly sampling frequency would be useful; a weekly sampling frequency allows a more accurate estimate of the episode periodicity but does not fit into the EMAP design. If symptoms are to be related to yield, index period may be the same as that for crop yield.

MEASUREMENTS: A field survey would assess plants for symptoms of fungal, bacterial, insect, and nutritional problems. The observations would include reporting and diagnosing pathogen presence or symptoms and a quantitative assessment (% cover) for plants with any reported symptom. This type of survey can provide general information on the health of a field or crop and specific information on the major disease and insect stresses that are present. The sampling density would depend on the desired data resolution and sampling frequency (Campbell and Duthie 1989). Some states may have pest survey data available.

Observers must be trained (40-50 h per observer) in the diagnosis of foliar symptoms and trained in calibration if quantification is required. Symptoms should be clearly described with photographs, if possible. Development of disease identification aids would cost $50-$100 for each crop. Data sheets should provide a standardized reporting format for easy transfer to a data base. The measurement is easy to acquire (in 30-60 min a sampling unit) and fairly inexpensive after training field crews. Field calibration and validation of foliar symptoms are necessary operations for field enumerators to reduce measurement error.

Foliar injury and mortality depress leaf area index values and increase the intensity of the lignin/cellulose absorption in plant canopies. Recent laboratory and airborne spectral measurements of near-infrared lignin/cellulose absorption suggest that spectral features of dry plant materials could be used to indicate vegetation stress.

VARIABILITY: The expected spatial variability of foliar symptoms within a resource sampling unit would produce a range that deviates 10-20% from the mean value; this deviation will be lower if presence versus absence (incidence) is used. The expected temporal variability of foliar symptoms during the index period might be great (coefficient of variation >50%).

PRIMARY PROBLEMS: If identification of a specific disease is required, it might be necessary to isolate the pathogen; however, common insect and disease problems can be identified with little or no ancillary data. Confirmation of symptoms of mineral deficiency or toxicity might require additional nutrient analysis data.

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F.8 INDICATOR: Agricultural Pest Density

CATEGORY: Exposure and Habitat/ Pathogens

STATUS: High-Priority Research

APPLICATION: Agricultural pest density is an indicator of the amount of biological stress to which the crops are exposed. If higher pest densities are monitored in agroecosystems that are in subnominal condition, it would support biological stress as a contributing cause to this undesirable status. Two types of pests or pathogens will be monitored: weeds and nematodes. Insects, fungi, and bacteria will probably be present as pests in agroecosystems as well; however, techniques for estimating the population densities of these pests or pathogens are not currently amenable to the EMAP sampling design, including the selection of an index period during which all sampling will occur. Indirect estimates of effective populations of insect pests and fungal and bacteria pathogens will be obtained from the "Visual Symptoms of Foliar Damage: Crops" indicator (F.7).

Weeds are defined as any plant present in an agricultural field other than the intended crop plant. The number of weed species present, particularly noxious weed species, indicates the effectiveness of pest management and cultural practices, as well as the potential stress to which the associated crop is subjected. The presence of certain noxious weeds (e.g., sicklepod [*Cassia obtusifolia*], witch weed [*Striga lutea*]) also indicates potential for a high degree of stress on the system.

Plant-parasitic nematodes are stylet-bearing nematodes that depend on a host plant for nutrition at one or more life stages. The population size of plant-parasitic nematodes can be related to a damage threshold or nematode hazard index for specific crops (Barker et al. 1985; Ferris 1978). Nematode assays and advisory services (Rickard and Barker 1982), available in several states in the Southeast, currently provide specific cultural and management recommendations for minimizing nematode damage to crop plants. Counts of plant-parasitic nematodes indicate success or failure of current season practices as well as potential for future losses.

INDEX PERIOD: The most appropriate time for an agricultural weed survey would be early in the growing season (spring to early summer), after crop emergence. The most appropriate index period for plant-parasitic nematodes would be at or near crop maturity. At crop maturity, usually in autumn, populations of most plant-parasitic nematodes are at their highest annual levels. The higher population levels maximize the probability of detection of rare but important species, and it is the autumn population levels that usually serve as a basis for damage threshold or hazard index determinations (Barker et al. 1985).

MEASUREMENTS: Weeds would be monitored in current-season production fields only, not in fallow or set-aside fields or in areas adjacent to production fields. Weeds would be identified by species, and a separate list would be prepared for each resource sampling unit. The enumerator would survey for weeds along a diamond-shaped sampling path (four transects or diagonals connecting the midpoints of the field edges). Weed species within visual range would be recorded on a minimum of five equally spaced stops along each diagonal. From this survey, the species number (richness) and the presence of any noxious weeds can be determined. Enumeration of weed species would require 0.5-1 h at each resource sampling unit. Because the weed information is merely an enumeration of species presence, a sufficiently representative sample should detect all species present.

The plant-parasitic nematode count in 500 cm^3 soil would be determined from one composite soil sample from each resource sampling unit. Soil would be collected with a sampling tube (at least 2 cm inside diameter) to a depth of 20 cm. Thirty cores taken in a zigzag pattern from at least three transects of a resource sampling unit would be well mixed, and a sample of at least 500 cm^3 would be submitted to a nematode assay laboratory (Barker and Campbell 1981). Nematodes would be extracted from the soil by an elutriation and centrifugal flotation procedure (Byrd et al. 1976; Barker et al. 1986). A dissecting microscope would be used to tally population size of each of the major parasitic species. The collection of soil samples for the nematode assay would require 0.5 h at each resource sampling unit. The estimated cost of a laboratory nematode assay is $5 per sample. For plant-parasitic nematodes, the compositing of the sample from at least 30 core samples should quantify variability adequately.

VARIABILITY: Some spatial variability in weed species present and in numbers of plant-parasitic nematodes present is expected within a resource sampling unit. If repeated samples of 30 cores were taken from the same field, after mixing and extraction, the coefficient of variability should not exceed 20% within most sampling units. The expected temporal variabilities of agricultural pests over a 2-3 week index period would produce a range that deviates <10% from the mean value.

PRIMARY PROBLEMS: Rare and isolated weed species may not be detected. Plant-parasitic nematodes may be detected less frequently in the Northeast, Central, Great Plains, and Northwest than in the Southeast because of the relative abundance of nematodes in these regions and because of the projected size of sampling units and the projected sampling frequency of the EMAP design.

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F.9 INDICATOR: Lichens and Mosses, Clover, Earthworm Bioassays

CATEGORY: Exposure and Habitat/ Bioassays

STATUS: High-Priority Research

APPLICATION: Lichens and mosses have been used for more than a century as biomonitors of air pollution. They are long-lived perennials lacking roots and cuticle; because they absorb most of their nutrients (and contaminants) directly from atmospheric deposition, they are ideal organisms to assess exposure to certain airborne chemicals. Several studies have used lichens and mosses as accumulators of heavy metal contamination around point-emission sources (Gilbert 1965; Manning and Feder 1980). They also may accumulate persistent agricultural organic chemicals, if these chemicals do not interfere with metabolism to cause dysfunction or death. Lichen and moss species differ in their sensitivity to SO_2 and other compounds; ecosystems that experience high ambient levels of air contaminants (specifically SO_2) can lose sensitive species. Lichen zone maps can indicate zones of SO_2 contamination downwind from a point source (Gilbert 1965). Lichens can also be transplanted into polluted zones for use in observing the extent and severity of the pollution problem.

A number of higher plants also have been used successfully as biomonitors of air pollution stress; examples are tobacco, potato, alfalfa, cotton, ragweed, soybean (Manning and Feder 1980; Ashmore et al. 1988; Kromroy et al. 1989). Recently, a monitoring system using an O_3 sensitive (S) clone and an O_3 resistant (R) clone of ladino clover has been developed to diagnose O_3 stress (Heagle et al. 1989). This system, which is designed to provide information on the temporal and spatial distribution of elevated O_3 and possibly other atmospheric pollutant levels, has the potential to serve as a monitor of atmospheric pollutant effects on yield of important crop species on a wider geographic and temporal basis than had been possible previously. The clover system also may be useful in developing a production index that includes short-term climatic variables.

Earthworms have a long history of use as indicator organisms because they occur in a majority of soils, are large and easy to identify, are in intimate contact with soil, take up moisture through their integument, and are noncontroversial experimental animals; these attributes make earthworms suitable for monitoring soil contamination. Earthworms make up a large proportion of the total biomass of soil invertebrates. They play a key role in the breakdown of decaying plant and animal material in the soil and maintain soil structure, aeration, and fertility. Earthworms are affected, via intake into their tissues, by a number of organic and inorganic contaminants.

INDEX PERIOD: The lichen-moss survey would occur in late summer or early autumn after application of pesticides and during the crop growing season. Clover would be monitored monthly during its growing season. Containers with contents of standardized parameters that relate to earthworm activity (soil, species, numbers, baseline measurements) would be placed by field crews in the spring; the assessment would occur upon their return in early autumn.

MEASUREMENTS: Lichens and mosses: Naturally occurring lichen and moss species could be surveyed, or transplants (lichen strings, lichen bark samples, moss bags) could be monitored for chemical input and accumulation or for presence or absence of the lichen and moss species (Gilbert 1965; Huchabee 1973). Lichen and moss collection would have a relatively low labor cost. Plant material would be dried and stored; chemical analyses of the material would be expensive. The recommended interannual sampling frequency for a lichen-moss survey is every year.

Clover system: The S and R clones of ladino clover were grown under several O_3 regimes; and foliar injury, leaf chlorophyll and biomass were compared (Heagle et al. 1989). The S/R ratio of these three measures was related to the O_3 concentration and could be calibrated to show their relationship to yield of important crop species as well as ambient O_3 concentrations. Clover would be monitored for biomass, visible injury, and leaf chlorophyll content. Mean seasonal results of clover biomass accumulation are used to perform correlation analyses with crop yields. Chlorophyll analysis needs only leaf clip - EtOH vials and a spectrophotometer; estimates of foliar injury require 0.5 h of a trained person for each resource sampling unit; and estimates of clover biomass require collection, drying, and weighing.

Earthworms: Enclosed field containers with a known species and count of earthworms would be monitored in both field crop and surrounding locations. Measurements would include population parameters such as mortality, reproduction, and growth and exposure parameters such as tissue chemical residues and biomarkers (see Appendix G-2) of enzyme induction (e.g., metallothionen) and enzyme depression (e.g., cholinesterases). The cost for constructing earthworm containers would be approximately $1.00 a plot, and containers could be reused. An adequate stock of earthworms would be inexpensive and easy to locate and maintain. Initial setup and final assessments (earthworm count per container; baseline chemical analyses) would be relatively laborious, and chemical and enzyme analyses would range from $100 to $1000.

VARIABILITY: The expected spatial variability of the bioassay measures within a resource sampling unit and temporal variability of the bioassays during the index period are not available for lichens and mosses, clover, or earthworms.

PRIMARY PROBLEMS: The ladino clover system needs some developmental time so that tests can be conducted on (1) the effects of climatic and edaphic factors on the O_3-induced S/R ratio, (2) the relative sensitivity of S and R clones to SO_2, other gases, parasites, and pests, and (3) calibrating clover response parameters to yield responses of crops.

Lichens, mosses and earthworms, used in a bioexposure mode (accumulation of contaminants), will not bioaccumulate all possible contaminants of concern. Many contaminants will not persist in biological tissues, but are transitory (e.g., ozone) and may or may not result in a biological response. More information about the physiochemical properties of contaminants, especially concerning pesticide active ingredients and other synthetic organics (including transformation products) is required to reduce analytical costs of contaminants. To provide contaminant flux (quantity/unit time) information, more research is needed to determine retention of initially absorbed contaminants.

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F.10 INDICATOR: Quantity and Quality of Irrigation Waters

CATEGORY: Exposure and Habitat/ Ambient Concentrations
Stressor/ Physical, Chemical

STATUS: High-Priority Research

APPLICATION: The quality of surface waters and ground water impacts productivity, sustainability, and overall condition of agroecosystems The concentrations of metals, salts, and toxic compounds are examples of aquatic parameters that could have deleterious effects on crops (indicator F.5) or livestock (indicator F.6). Some of these contaminants are already monitored through the National Stream Quality Accounting Network (NASQAN) of the U.S. Geological Survey (USGS) and through individual state departments of water resources. Ground-water quality is monitored by the USGS in cooperation with state agencies through the Federal-State Cooperative Water-Resources Program (Gilbert and Mann 1988). The USGS also maintains a variety of data bases in its Water Resources Division (USGS 1983).

The quantity of irrigation water available to agroecosystems may also stress the system and often serves as an indicator of sustainability of farming practices. When water is consumed faster than it can be replaced, the marginal cost eventually exceeds the possible return, and continued operation cannot be sustained.

Irrigation water inputs for western U.S. water districts can be tracked through the U.S. Bureau of Reclamation (1987). In addition, remote sensing techniques can be used to determine the number and extent of small streams and farm impoundments within or adjacent to a resource sampling unit. Ground-water quantity is monitored by the USGS through numerous programs. USGS conducts the Regional Aquifer Systems Analysis program, which focuses on defining regional hydrology and geology and establishing a framework of background information of geology, hydrology, and geochemistry of the nation's important aquifer systems (Sun 1985).

Depending on whether the parameters are obtained from the EMAP resource sampling units or from other established networks, water quantity and quality can be either exposure or stressor indicators for the EMAP-Agroecosystems indicator strategy.

INDEX PERIOD: Water quality parameters should be examined just before or during irrigation; water quantity should be examined before heavy water use.

MEASUREMENTS: The acquisition of instrumentation necessary to collect and analyze samples would be relatively costly; thus a thorough investigation of the utility of available data bases is warranted. Numerous efforts have been undertaken to inventory available data bases that could help support EMAP (Olson et al. 1989; Olson and Breckenridge 1989). Coordination with EMAP-Inland Surface Waters (Appendix B) would be imperative. Assuming remote sensing data are available from EMAP-Characterization, effort and cost would be <$10 a sample for water quantity determinations. Bureau of Reclamation data are summarized annually for western states (U.S. Bureau of Reclamation 1987). The National Weather Service has precipitation data which would be useful for areas that do not rely on irrigation.

If USGS data are being collected, the approximate data acquisition costs per resource sampling unit would include 4 h of a technician and 2 h of a scientist. If USGS data are not being collected, the resources would increase to about $800 for water analysis and 16 h of a technician and 4 h of a scientist to collect, analyze, and interpret data. Measurement error for most water parameters should be low because most require only simple, physical measurements. The recommended interannual sampling frequency is every year for water quality parameters and five years for water quantity measures.

VARIABILITY: The expected spatial and temporal variabilities of ground-water levels, surface water storage, and water quality within a resource sampling unit and during the index period, respectively, are not available. The variability associated with surface water storage data would be related mostly to climatic factors (e.g., snowfall, evapotranspiration rates). Water quality will be more variable because of differing management practices (e.g., timing of manure spreading).

PRIMARY PROBLEMS: Potential lack of coincidence of optimum index period with that of other EMAP-Agroecosystem indicators may necessitate an additional visit to a resource sampling unit if existing data bases cannot be utilized.

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F.11 INDICATOR: Soil Productivity Index

CATEGORY: Exposure and Habitat/ Ambient Concentrations

STATUS: High-Priority Research

APPLICATION: Each soil has a productivity capacity for a specific crop or sequence of crops under a defined set of management practices. Soils high in organic matter and nutrients, of medium texture, and in good tilth, and of 150-cm (59.1-in.) depth are recognized as highly productive. Key site characteristics could be combined into a soil productivity index (SPI) that, if combined with the other exposure indicators, could be useful in assessing the causes of subnominal condition within an agroecosystem resource class.

Several scientists have made major progress in development of an SPI (Pierce et al. 1983, 1984). The effect of accumulated erosion on the potential productivity of different soil types has been considered. These data show that agricultural practices can impact soils slowly or fairly rapidly. For three different soil types investigated, the soils could remain at a sustained level for some time; however, under improper management the surface soil could be eroded away to expose the less productive subsoil.

The development of an SPI along with an erosion index could generate data like those presented in Figure F-1; these data show the major difference in the productivity index (PI) for three different soil series in Minnesota. An SPI developed with additional soils data (e.g., remote sensing data on crop residues) could

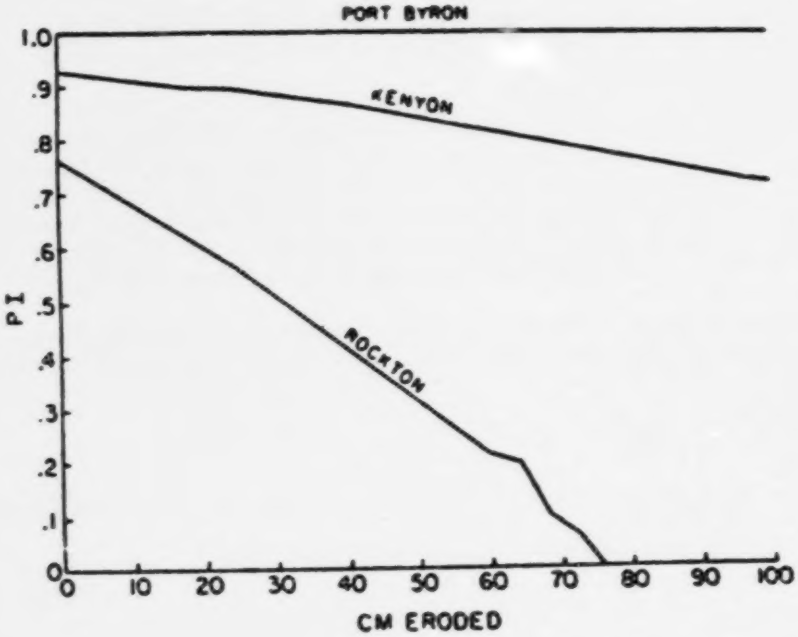

Figure F-1. An example of the potential use of soil productivity index and information on erosion rates for three soil series in Minnesota to illustrate the relative vulnerability of soils to erosion and the potential use of selected soil series as sensitive indicators (Source: Pierce et al. 1983).

be an important exposure indicator for agroecosystems. Soil series that are more vulnerable to degradation could serve as early-warning sites because they would be the first to display subnominal impacts from mismanagement.

The information in Figure F-1 demonstrates how available soils data can be applied in ecological assessments. In a recent commentary, Dregne (1989) concluded that a wealth of information is available from local, state, regional, and national sources. The study noted, however, that in only one area of the United States has research been conducted on the effect of soil loss on potential soil productivity within a large geographic area. This region covers about 800,000 ha (2 million acres) in the Palouse landscape of Washington and Idaho. The investigators of the Palouse study (Krauss and Allmarai 1982) concluded that over the past 90 years of farming, soil productivity has decreased by about 22% because of topsoil losses. By using an SPI in combination with erosion data (Indicator F.2), this type of assessment could determine the productivity of agricultural soils.

INDEX PERIOD: Soil samples and remote sensing data should be collected in autumn, preferably after fall management practices. Some of the soils data (i.e., texture, clay fraction) are not dependent on a season or event and can be collected during any unfrozen period.

MEASUREMENTS: Important factors that need to be considered in an SPI include soil rooting depth, topsoil thickness, available water capacity, texture, bulk density, permeability, clay fraction, pH, and soil organic matter content (includes crop residue). Approximate labor required to collect soil samples from a field (sampling unit of about 40 ha [100 acres]) would be 8 h of a technician and 2 h of a scientist. Estimated analysis cost is $3000 per soil series. The interannual sampling frequency would be 5 years or longer.

Data are generally not available on soil productivity; however, data bases like the SOILS-5 and the National Resources Inventory (NRI) have been established by the U.S. Soil Conservation Service since 1977 and can serve as input to an SPI.

VARIABILITY: Some of the soil factors needed to calculate an SPI for a soil series would be considered constant throughout the series (i.e., texture, depth). Although some physical and chemical parameters would be temporally variable (e.g., pH, bulk density), procedures to determine ranges and averages for most soil series have been established. The expected spatial variability of an SPI within a resource sampling unit would produce a range that deviates about 20% from the mean value. The expected temporal variability of SPI during the index period would produce a range that also deviates about 20% from the mean value.

PRIMARY PROBLEMS: Some developmental research is needed to combine the designated measurements into the soil productivity index. The importance of each factor would need to be evaluated on a soil series and regional basis.

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APPENDIX G: INDICATORS OF RELEVANCE TO MULTIPLE RESOURCE CATEGORIES

APPENDIX G.1: INDICATOR FACT SHEETS FOR ANIMALS

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G.1.1 INDICATOR: Relative Abundance: Animals

CATEGORY: Response/ Community Structure
Exposure and Habitat/ GEMs-Exotics

STATUS: High-Priority Research

APPLICATION: The ecological condition of a community can sometimes be assessed by the condition of a few species or categories of species (guilds) that play critical roles. Although the indicator species concept has not fared well in recent reviews (Landres et al. 1988), many ecologists agree that attention to particular species is valuable for community-level monitoring. The relative abundance, or where more feasible presence/absence, of species including exotics, keystone species, and sensitive species (e.g., listed threatened and endangered species) in a community should be tracked as an index of community condition. This indicator is related to many environmental values, including aesthetics, biodiversity, productivity, and sustainability.

To begin addressing which species or guilds should be monitored in each ecological resource class, EMAP hosted an animal indicator workshop in March 1990 that included a select group of biologists and ecologists whose specialties together spanned a range of animal types. The result of the workshop suggested certain animal types as appropriate indicators for each ecological resource category, based on the EMAP indicator selection criteria and field experience. Their relative ranking of animal types by these criteria and subsequent recommendations are summarized in Tables 9-2 and 9-3, respectively. Because of their consistently high relative score among all resource categories, birds were selected as the animal type that should be measured in all categories. Likewise, the low relative marks for large mammals and snakes prompted their elimination from immediate consideration. The nonavian vertebrate and invertebrate types that were suggested as appropriate indicators of the animal condition in each ecological resource category or subcategory are as follows:

Inland Waters
Vertebrate: Turtles, Frogs, and Salamanders
Invertebrate: Snails

Wetlands
Vertebrate: Turtles, Frogs and Salamanders
Invertebrate: Snails/Slugs

Coniferous Forests
Vertebrate: Salamanders
Invertebrate: Ground-Dwelling Beetles and Snails & Slugs (Northwest only)

Deciduous Forests
Vertebrate: Salamanders and Lizards (Southwest only)
Invertebrate: Ground-Dwelling Beetles, Ants, and Snails & Slugs

Tundra
Vertebrate: Small Mammals
Invertebrate: Bees

Arid Shrublands and Grasslands
Vertebrate: Lizards and Tortoises
Invertebrate: Grasshoppers, Ants, Termites, and Ground-Dwelling Beetles (Great Basin only)

Mesic Shrublands
Vertebrate: Small Mammals and Lizards
Invertebrate: Butterflies and Ants

Mesic Grasslands
Vertebrate: Small Mammals and Lizards
Invertebrate: Grasshoppers, Ground-Dwelling Beetles, and Termites

Agroecosystems
Vertebrate: Small Mammals
Invertebrate: Grasshoppers and Bees

INDEX PERIOD: The optimal sampling window during a year depends on the season of peak activity of the species to be sampled. The suggested sampling season is spring for **lizards, tortoises, frogs, toads, salamanders,** and **bees**; summer for **turtles** and **termites**; late summer for **small mammals** and **grasshoppers**; early and late summer for **butterflies**; and spring to autumn for **ground-dwelling beetles, snails/slugs**, and **ants**. The suggested window for **birds** is a month in duration and depends on latitude, ranging from May in the South to early July in the North. Sampling should be avoided during moonlit nights and stormy weather.

MEASUREMENTS: Relative abundances or presence/absence of the identified animal types would be determined by means of standard sampling techniques for the taxa; a leading sampling technique for **small mammals, ground-dwelling beetles, lizards, frogs, toads, salamanders**, and some **ants** includes use of permanent pitfall can traps (opened only for optimal sampling periods). The pitfall traps would contain ethylene glycol to kill and preserve the specimens between site visits. The sampling technique for **snails** and **slugs** uses small squares of untreated lumber, whereas the technique for **ants** and **termites** involves placing toilet paper rolls in the traps. Standard sweep-sample techniques currently exist for sampling **grasshoppers**, but sticky traps may become the standard grasshopper collection technique in the future. **Bees** and **butterflies** can be collected by netting along line transects; colony bees can be collected from hives, and cavity-nesting bees can be sampled by using wood blocks with holes.

The most cost-effective census technique for **birds** would be point counts, whereby a trained observer notes all birds seen or heard during a specified length of time (usually 5-15 min). A trained birder can perform 5-10 point counts in one morning; ideally three replicates should occur annually at a point. Another possible indicator taxon with high mobility is the **bat**; a sampling technique is being developed that utilizes tape recorders with photocells that record bat sonar at set intervals. Tape recorders are also being investigated for use in bird censusing.

For animal types other than birds, approximately 30 stations for each sampling technique would be placed along a line transect within a resource sampling unit. Stations must be located both in the center and edge areas of this sampling unit. These provide relative abundances, when all species in the taxonomic or functional group of interest are tallied from the sample. Absolute abundance, on the other hand, requires intensive mark-recapture or repeated observations, which are cost-prohibitive over large geographic regions. The recommended interannual sampling frequency would be four years.

VARIABILITY: The spatial variability of relative species abundances or presence/absence within a resource sampling unit using common techniques would be dependent on the taxa sampled. The expected temporal variability of relative species abundances during the index periods would also be dependent on taxa.

PRIMARY PROBLEMS: (1) Abundances of all but the most conspicuous species (such as large birds and mammals in open habitats) are notoriously difficult to assess with accuracy; however, standardized census techniques allow valid comparisons for a site (or better yet, a series or group of sites) over time. (2) Pitfall traps result in the destructive sampling of organisms. Sherman live traps can be used for small mammals; however, live traps would not be as cost-effective because they are not permanent, capture fewer animals, and require more frequent site revisitation. Destructive sampling, however, will enable the possible application of other indicator types (e.g., contaminants in tissues and biomarkers) and removes animals at a resource sampling unit only once every four years. (3) Bird point counts introduce a bias toward calling birds. (4) Presence/Absence measurements contain less information that relative abundance but may be logistically more feasible for EMAP.

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G.1.2 INDICATOR: Demographics: Animals

CATEGORY: Response/ Population Structure

STATUS: Research

APPLICATION: Population vigor is reflected in the recruitment of individuals (birth rate and their survivorship) into and through the breeding population. Analysis of demographic variables such as age structure, sex ratio, fertility, mortality, survivorship, and dispersal may be particularly worthwhile for populations of keystone species that are known to be sensitive to a particular disturbance. These measurements are the traditional tools of animal biologists and managers for assessing population "health" (Schemnitz 1980).

INDEX PERIOD: The optimal sampling window during a year depends on species to be sampled, but should be within the season of peak activity regardless. The suggested index periods for each animal type are listed under Indicator G.1.1.

MEASUREMENTS: A detailed life table is informative but its construction is laborious. Estimates of fertility and mortality (birth and death rates) can be obtained through observations or estimates, especially of marked individuals. Dispersal may be difficult to document with the EMAP sampling design. For species that can be separated into general age classes, a portrayal of the age structure of the population may be a good indicator. Temple and Wiens (1989) suggest that primary population parameters (birth, death, and dispersal rates) for birds may provide a better indication of response to environmental change than secondary population parameters (population size, density, habitat occupancy, age structure, sex ratio, proportion of breeders). In addition, numerous studies of bird nesting and fledgling success have revealed that these may be sensitive indicators of response to stress. Many fish and game agencies collect information on sex ratio, density, birth/death, harvest, and dispersal rates. This data could supplement data collected by EMAP resource groups. The recommended interannual sampling frequency is three or four years, although some parameters may need more frequent monitoring.

VARIABILITY: The expected spatial and temporal variabilities of demographic parameters within a resource sampling unit and during the index period, respectively, were not estimated because specific demographic parameters, species, and individuals were not defined explicitly.

PRIMARY PROBLEMS: Most demographic variables can be measured only through detailed study. EMAP observations are expected to be limited to no more than two brief field visits at a resource sampling unit in any given year, so demographic parameters will probably not be estimated. When primary population parameters are used, it is important to look for compensatory effects (e.g., an increase in mortality accompanied by an increase in fecundity or survivorship). If secondary population parameters are used, then time lags, site fidelity, and compensation may prevent short-term responses to environmental perturbations from being noticed (which is sometimes helpful, but also obscures response to certain stressors).

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G.1.3 INDICATOR: Morphological Asymmetry: Animals

CATEGORY: Response/ Population Structure

STATUS: Research

APPLICATION: Fluctuating asymmetry (FA) is the morphological variability demonstrated by an individual organism. FA in structures of bilaterally symmetrical organisms (e.g., fin rays, teeth, limb bones, fingertip ridges, wing length) can be an early-warning indicator of population responses to environmental and genetic stress. The application of this indicator may be worthwhile for species that are known to be sensitive to a particular disturbance, including exposure to pesticides, heavy metals, and other pollutants, hybridization, and inbreeding; each has been found to result in FA for various species.

INDEX PERIOD: The optimal sampling window during a year depends on species to be sampled, but should be within the season of peak activity. The suggested index periods for each animal type are listed under Indicator G.1.1.

MEASUREMENTS: No single character may provide an adequate measure of response; hence, a composite index containing information from several characters is preferred. Many of these indices, including their statistical strengths and weaknesses, are discussed by Palmer and Strobeck (1986). Leary and Allendorf (1989) note that relatively sedentary organisms (closely associated with a local environment) and ectotherms (whose development may be more sensitive to environmental and genetic variation) may be the best candidates for measurement of FA. The recommended interannual sampling frequency is four or five years.

VARIABILITY: The expected spatial variability of the fluctuating asymmetry index within a resource sampling unit was not estimated because the index and species were not explicitly defined; however, the relationship of FA with character size is troubling, as variance increases with increasing character size. Because differences in FA among samples are usually small, confounding factors such as measurement error can be important. The expected temporal variability of demographic parameters during the index periods was not estimated because index periods were not defined explicitly.

PRIMARY PROBLEMS: Measurement error may be the largest obstacle in discriminating differences in FA among populations; however, a rigorous quality management program can keep such errors to a minimum.

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APPENDIX G.2: INDICATOR FACT SHEETS FOR BIOMARKERS

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G.2.1 INDICATOR: DNA Alteration: Adducts

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: Recent field studies (Dunn et al. 1987; Varanasi et al. 1989; Stein et al. 1990) with benthic fish have begun to validate the use of DNA adducts (using the ^{32}P-postlabeling assay technique) as a biomarker of exposure to genotoxic compounds. For example, comparison of the levels of total hepatic DNA adducts in English sole from Puget Sound, Washington, to sediment levels of high-molecular-weight polycyclic aromatic hydrocarbons revealed a general concordance between these variables that suggests that adduct counts appear to be reflective of the degree of exposure (Varanasi et al. 1989; Stein et al. 1990).

The ^{32}P-postlabeling technique shows particular promise as a screening technique because it has a very low limit of detection (one adduct in 10^{9}-10^{10} nucleotides) and does not require the characterization of individual adducts before they are measured. A further important advantage is that it is a nonspecific procedure that can detect a variety of bulky aromatic adducts in animals exposed to complex mixtures of contaminants. Although a positive response is indicative of exposure to chemical(s), with sufficient toxicological information and identification of particular adducts, data obtained by this technique may be diagnostic of environmental genotoxicity.

The technique can be implemented immediately with little or no lag time; however, only a few "dedicated" laboratories are currently available to perform this type of analysis. The geographical range of test species within a resource class must be considered.

INDEX PERIOD: No temporal limitations are known to exist; however, no sampling period during the year is known to have minimal temporal variability in adduct measures.

MEASUREMENTS: DNA adducts, enzymatically tagged with a radiolabeled component [^{32}P], are separated by thin-layer chromatography (TLC), detected by autoradiography, and quantified by Cerenkov counting (Randerath et al. 1981; reviewed by Watson [1987]). In this procedure (summarized by Gupta and Randerath [1988]), DNA is enzymatically hydrolyzed to 3'-monophosphates of normal DNA nucleotides and adducts. The adducts are then enriched relative to the normal nucleotides, ^{32}P label is incorporated (leading to [5'-^{32}P]-3',5'-biphosphates), and the remaining normal nucleotides and adducts are separated by multidimensional TLC. Finally, the adducts are detected by autoradiography and quantitated by scintillation counting. Sample collection times for a suite of biomarker indicators is 0.5-1.0 day at each resource sampling unit for two to three technicians. The estimated laboratory analysis cost for DNA adducts is $150-$200 per sample.

VARIABILITY: The expected spatial variability of adduct measures within a resource sampling unit and their temporal variability throughout the year were not estimated.

PRIMARY PROBLEMS: Although the cost is moderate, the ^{32}P-postlabeling assay is currently more laborious than other biomarker-type assays, requires substantial training of personnel before it can be routinely used, and involves the use of high-specific-activity ^{32}P, which necessitates the use of special precautions to minimize exposure to radioactivity. Additionally, this technique is semiquantitative, and generally the procedure for its use varies from one laboratory to another. Finally, in TLC chromatograms of DNA from organisms exposed to complex mixtures of contaminants, a radioactive zone is routinely observed, which appears to represent multiple overlapping adducts and makes it difficult to relate individual spots (adducts) to specific chemicals. Recent advances in chromatographic conditions (Randerath et al. 1989), however, suggest that the resolution of multiple adducts can be increased, which should aid in characterizing individual adducts in organisms exposed to unknown mixtures of chemicals, and thus may increase the chemical specificity of the ^{32}P-postlabeling assay.

A recent study by Kurelec et al. (1990) illustrates, however, the need for further in-depth field studies of DNA adducts as a biomarker of exposure to genotoxic compounds. In this study, five species of fish exhibited several qualitatively similar adducts irrespective of whether the fish were sampled from apparently unpolluted or polluted sites. These findings emphasize the need to conduct future field validation studies that incorporate additional measures of contaminant exposure in individual organisms in order to clearly demonstrate that the levels of DNA adducts are related to exposure. Furthermore, these studies illustrate a disadvantage of the ^{32}P-postlabeling assay, in that careful selection of appropriate control sites is a critical factor in the current use of this technique for measuring DNA adducts.

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G.2.2 INDICATOR: DNA Alteration: Secondary Modification

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: Numerous toxic chemicals cause strand breaks in DNA, either directly or indirectly which causes an unwinding or secondary modification of the DNA molecule. The alkaline unwinding assay can estimate the increase in the level of breaks above background that result from exposure to toxins. The technique can be applied to the analysis of many samples without the need for costly reagents or laboratory equipment. For field studies, laboratory analyses are performed on live animals or frozen tissues. Data is available within a few hours and is best interpreted along with data collected from other biomarkers. The method is ideally suited as a *screening technique* for the routine *in situ* monitoring of environmental species because the analysis is easy and its cost is low. A positive result can be seen as a "red flag," because in theory, exposure to any genotoxic chemical will elicit such a response.

Using this method, Shugart (1988a,b) has demonstrated that alkaline unwinding is significantly faster in the DNA of fish that were chronically exposed to genotoxic agents than in control fish. Additionally, it was shown that fish DNA from polluted areas unwound faster than DNA of fish from nonpolluted areas, indicating sensitivity to xenobiotic substances in their environment (Shugart 1990). In addition, analyses have been conducted in numerous environmental species including oysters and mussles (Nacci and Jackim 1990), desert rodents (Shugart 1989), and turtles (Meyers et al. 1988).

The method is sensitive, amenable to routine laboratory analyses, and immediately available for field studies. The geographical range of test species within resource classes must be considered.

INDEX PERIOD: No temporal limitations are known to exist; however, no sampling period during the year is known to have minimal temporal variability for measuring this indicator.

MEASUREMENTS: Alkaline unwinding is a sensitive analytical technique which has previously been used in cell cultures to detect and quantify DNA strand breaks induced by physical and chemical carcinogens (Ahnstrom and Erixon 1980; Kanter and Schwartz 1979, 1982; Daniel et al. 1985). To assess the level of DNA strand breaks in environmental species intact, highly polymerized DNA is required (Shugart 1988a,b). DNA isolation is accomplished by homogenizing appropriate tissue in 1 N NH_4OH/0.2% Triton X-100. DNA is recovered by differential extraction with chloroform/isoamyl alcohol/phenol (24/1/25-v/v) and passage through a molecular sieve column (Sephadex G50). Strand breaks are measured in the isolated DNA by an alkaline unwinding assay (Kanter and Schwartz 1979, 1982; Shugart 1988a,b). The technique is based on the time-dependent partial alkaline unwinding of DNA followed by determination of the duplex:total DNA ratio (F value). Because DNA unwinding takes place at single-strand breaks within the molecule, the amount of double-stranded DNA remaining after a given period of alkaline unwinding will be inversely proportional to the number of strand breaks present at the initiation of the alkaline exposure, provided renaturation is prevented. The amounts of these two types of DNA are quantified by measuring the fluorescence that results with bis-benzimidazole - Hoechst dye #33258. Test response is quite sensitive to toxins, and changes are readily discerned, provided proper baseline or reference data is available.

Rydberg (1975) has established the theoretical background for estimating strand breaks in DNA by alkaline unwinding, which is summarized by the equation:

$$\ln F = -(K/M)(t^b)$$

where K is a constant, t is time, M is the average molecular weight between two breaks, and b is a constant less than 1 which is influenced by the conditions for alkaline unwinding.

The relative number of DNA strand breaks (N value) of an organism from a control site can be compared to that from a reference site as follows (Kanter and Schwartz, 1982; Shugart, 1988a,b):

$$N = (\ln F_c / \ln F_r) - 1$$

where F_c and F_r are the mean F values of DNA from the control site and reference site, respectively. N values greater than zero indicate that DNA from the sampled sites has more strand breaks than DNA from the reference site; for example, an N value of 5 indicates five times more strand breakage.

Sample collection times for a set of biomarker indicators is 0.5-1.0 day at each resource sampling unit for two to three technicians. The estimated laboratory analysis cost for alkaline unwinding is $25 a sample.

VARIABILITY: Existing data suggest the spatial variability of this indicator within a resource sampling unit would be low. Its expected temporal variability throughout the year was not estimated.

PRIMARY PROBLEMS: No major problem is known to exist that would prevent its immediate use in the field.

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G.2.3 INDICATOR: DNA Alteration: Irreversible Event

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: The measure of irreversible DNA alteration is a screening technique that indicates subclinical expression of mutagenic damage.

INDEX PERIOD: No constraints on the sampling period are recognized. Because the period with minimum temporal variability is unknown, no index period has been suggested.

MEASUREMENTS: Flow cytometry (FCM) measures various cellular variables in suspended cells (Shapiro 1988). Measurable variables include levels of DNA, RNA, protein, and specific chemicals (using immunofluorescent probes), and numerous morphological attributes that affect time of flight and various light-scatter parameters. Some flow cytometers can analyze as many as eight parameters from 10,000 cells a second. Cell-sorting capabilities are available on many flow cytometers.

The application of flow cytometry to the study of environmental mutagenesis was reviewed by Bickham (1990). The primary parameter of interest in such studies is DNA content, which can be measured with a high degree of precision and accuracy. Laboratory challenge experiments have shown that exposure to mutagenic chemicals and ionizing radiation result in a broader nuclear or chromosomal DNA distribution; a positive relationship between exposure and a broader distribution exists, both *in vivo* (Bickham 1990) and *in vitro* (Otto et al. 1981). Bickham (1990) concluded that FCM is a highly sensitive assay for the effects of environmental mutagens. Advantages of FCM over other cytogenetic and cytometric techniques include lower cost, greater rapidity, greater sensitivity due to the vast number of cells analyzed, and tremendous diversity of application to which FCM is suitable. For example, virtually any tissue can be examined (whereas chromosomal assays are limited to rapidly proliferating tissues such as bone marrow), so the effects of organ-specific mutagens can be investigated. With the use of multiparameter analysis, specific cell types can be differentiated and analyzed. Moreover, FCM is easily adapted for use on species in which chromosomal analysis is difficult (Bickham et al. 1988; Lamb et al. 1990).

FCM has also identified a potential qualitative difference in the response of animals to chronic environmental and acute laboratory mutagen exposure. Aneuploid mosaicism was observed in animals exposed at low frequency to environmental mutagens in each of three studies (McBee and Bickham 1988; Bickham et al. 1988; Lamb et al. 1990). Such mosaicism was not observed in animals from control sites or in animals exposed to acute laboratory doses (Bickham 1990). This demonstrates the capability of FCM to identify multiple populations of cells that might have subtle differences in DNA content and to identify low-frequency variant cells.

For use as an initial screening procedure, FCM has tremendous potential because of low cost and high sensitivity. Hundreds of thousands of cells from scores of individuals can be analyzed quickly, in a matter of a few days if necessary. This techniques can be useful both in the initial screening for effects and in the subsequent evaluation of the level of damage of environmental mutagens. FCM can also be used to evaluate almost any species and tissue type, so the degree of impact of an environmental insult can be investigated. Sample collection times for a set of biomarker indicators is 0.5-1.0 day at each resource sampling unit for two to three technicians. The estimated laboratory analysis cost for flow cytometry is $25-$75 a sample.

VARIABILITY: FCM has been extensively validated as a laboratory procedure for evaluating acute exposure to mutagenic chemicals. Field studies have demonstrated the efficiency of FCM in measuring the effects of chronic exposure to chemical pollutants (McBee and Bickham 1988) and low-level radioactivity (Bickham et al. 1988; Lamb et al. 1990). The expected spatial variability of this indicator within a resource sampling unit and its expected temporal variability throughout the year were not estimated.

PRIMARY PROBLEMS: No major problem is known that would prevent its immediate use.

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G.2.4 INDICATOR: Cholinesterase Levels

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: The diagnosis of exposure to neurotoxic chemicals such as organophosphates and carbamates (insecticides) usually relies on the measurement of acetylcholinesterase (ACh-ase) activity, because inhibition of this critical enzyme is the mechanism by which these agents exert their neurotoxic effect. Measurement of ACh-ase activity not only monitors physiological response; the technique is also diagnostic because the enzyme activity can be compared to results from previous studies on the sublethal and lethal effects of these neurotoxic chemicals in a variety of vertebrates and invertebrates. Use of brain tissue is considered the most reliable approach because inhibition most closely correlates with other toxic effects, including mortality. However, nondestructive, sequential sampling can be accomplished in a single individual by examining blood for ACh-ase activity. Such repeated measures can be useful in a field situation to document exposure and subsequent recovery. It is anticipated that the degree of ACh-ase depression from normal levels could be used as an integrative, functional, nondestructive measure of exposure.

There is extensive literature available that is useful for interpreting ACh-ase activity data in a variety of species (e.g., Fairbrother et al. 1989). The biomarker has been extensively field tested.

INDEX PERIOD: An important consideration is the effect of generally short half-lives of organophosphorous compounds and carbamates (in the environment and in biological tissues) on the duration of ACh-ase activity. Seasonal effects also are a factor.

MEASUREMENTS: ACh-ase activities are measured in brain tissue and blood plasma. Ellman et al. (1961) is a generally cited reference describing the ACh-ase assay that is currently undergoing the American Society for Testing and Materials (ASTM) standardization process. For monitoring avian and fish exposures, greater than 20% inhibition of ACh-ase activity has been used as an index for significant exposures and greater than 50% inhibition as indicative of lethal exposures. Sample collection times for a set of biomarker indicators is 0.5-1.0 day for each resource sampling unit for two to three technicians. The estimated laboratory analysis cost for measuring ACh-ase activity is $25-$75 a sample.

VARIABILITY: ACh-ase activity can be affected by physiological factors, and these need to be considered in interpreting data. The expected spatial variability of Ach-ase measures within a resource sampling unit and their temporal variability during the year were not estimated.

PRIMARY PROBLEMS: No major problems are recognized.

REFERENCES:

Ellman, G.L., K.D. Courtney, V. Andres, and R.M. Featherstone. 1961. A new and rapid colorimetric determination of acetylcholinesterase activity. Biochem. Pharmacol. 7:88-95.

Fairbrother, A., R.S. Bennett, and J.K. Bennet. 1989. Sequential sampling of plasma cholinesterase in mallards as an indicator of exposure to cholinesterase inhibitors. Environ. Toxicol. Chem. 8:117-122.

G.2.5 INDICATOR: Metabolites of Xenobiotic Chemicals

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: The identification of certain metabolites of xenobiotic chemicals in animals confirms that toxicants have entered cells and interacted with molecular targets; in this way, supporting evidence can be provided that a population response is attributable to biochemical stress from xenobiotic compounds. These metabolite biomarkers can be used to assist in such diagnoses since the nature and proportions of metabolites of xenobiotic chemicals in various tissues have been extensively studied (Creaven et al 1965; Lee et al. 1972; Melancon and Lech 1976; Krahn and Malins 1982).

The feasibility of using xenobiotic metabolite formation as a biomarker depends on the sensitivity of the analytical methods employed for their detection and quantitation. The presence of such metabolites may be assessed by detection and quantitation of free and conjugated metabolites in tissues, body fluids, or excreta. Determination of the metabolites of polycyclic aromatic hydrocarbons (PAHs) in tissues and of PAHs and chlorinated phenols in bile of fish as a biomonitoring method is currently ready for use in environmental monitoring (Lee et al. 1972; Krahn and Malins 1982).

INDEX PERIOD: If measurements of metabolites are to be undertaken in wild populations of organisms, initial sampling efforts must be designed so that temporal variability throughout the year can be tested. Also, variability in feeding times (e.g., in the case of biliary metabolites), sex, maturity, and environmental temperatures are ancillary factors that must be considered, any of which may dictate a stratified sampling program. Several treatments of environmental sampling design are available that can be used to help in design of a statistically sound sampling strategy.

MEASUREMENTS: Most of the analytical procedures used for measuring free and conjugated metabolites involve chromatographic techniques including gas chromatography and high-pressure liquid chromatography (with or without enzymatic hydrolysis). A limitation of many of these procedures is the lengthy preparation time required before the sample is subjected to analysis. Thus, the efficiency and cost-effectiveness of metabolite biomarkers could be significantly improved by developing procedures such as an immunoassay for sensitive, rapid measurement of metabolites in a large number of samples.

A variety of factors, including reproductive state, temperature, and dietary status, can influence metabolite production. The influence of various factors on metabolite proportions has been the focus of more limited studies. For example, during feeding, the bile and its associated metabolites are discharged from the gall bladder. In females during egg production, a number of biochemical changes occur that can affect production of metabolites. These include steroid-synthesizing cytochrome P-450 isozymes that can affect oxidation rates of xenobiotics and types of metabolites produced. Also, there is increased lipid synthesis needed for egg production, which may facilitate metabolite production. Eggs may sequester certain types of metabolites. Ancillary measures of these influential factors must be made to account for their effects on metabolite production.

Sample collection times for a set of biomarker indicators is 0.5-1.0 day for each resource sampling unit for two to three technicians. The estimated laboratory analysis cost for metabolite measures is $25-75 a sample.

VARIABILITY: The expected spatial variability of metabolite measures within a resource sampling unit was not estimated. The expected temporal variability of metabolites was not estimated because the index period was not defined; however, the temporal variability could be significant because of the relatively rapid pharmacodynamics of many metabolites. Nevertheless, field trials have demonstrated clear statistical differences between exposed and unexposed populations (Melancon and Lech 1976; Krahn and Malins 1982).

PRIMARY PROBLEMS: Species-specific information is needed to expand the utilization of metabolites as biomarkers beyond fish and the aquatic environment. In addition, if metabolites are to be used as biomarkers of effect, more information is needed to relate the presence of specific metabolites of xenobiotics in organisms to toxic effect.

REFERENCES:

Creaven, P.J., D.V. Parke, and R.T. Williams. 1965. A fluorometric study of the hydroxylation of biphenyl in vitro by liver preparations of various species. Biochem. J. 96:879-885.

Krahn, M.E., and D.C. Malins. 1982. Gas chromatographic-mass spectrometric determination of aromatic hydrocarbon metabolites from livers of fish exposed to fuel oil. J. Chromatogr. 248:99-107.

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G.2.6 INDICATOR: Porphyrin Accumulation

CATEGORY: Exposure and Habitat/ Tissue Concentration

STATUS: Research

APPLICATION: Heme biosynthesis is a vital process for animals to maintain an adequate blood cell count, because the heme molecule is the building block for blood cells. When a chemical is known to have a specific effect on heme biosynthesis, abnormalities of porphyrin metabolism may provide a method for assessing exposure (Elder and Urquhart 1987). Conversely, patterns of porphyrin accumulation in tissues and excreta may be used to predict the sites of action of chemicals within the pathway of heme biosynthesis (Marks 1985). Thus the analyses of porphyrins may be used in a diagnostic manner.

Chlorinated aromatics such as polychlorinated biphenyls (PCBs) and heavy metals such as Pb may disturb porphyrin metabolism in mammals and birds. In chemically induced porphyrias, these chemicals or their metabolites modify the activity of one or more of the enzymes involved in heme biosynthesis, resulting in an alteration in the size and/or composition of the porphyrin pool (Goldstein et al. 1973; Strik 1979). Available evidence in birds suggests that porphyrins are promising as a biomarker in field studies. This biomarker is currently accepted as a biomarker in human studies.

INDEX PERIOD: No temporal limitations are known to exist; however, no index period during the year is known to have minimum temporal variability.

MEASUREMENTS: Analysis involves homogenizing the liver in 3 N HCl to extract the porphyrins and determining individual protoporphyrins by their fluorescence. Uroporphyrin can be determined directly on the HCl extract by its specific fluorescence. The spectrum of protoporphyrins present can be determined by high-pressure liquid chromatography with fluorescence detection.

An example of the use of porphyrins in ecological studies is exposure of mallard ducks to Pb. Pb inhibits the activity of heme synthetase, the enzyme responsible for incorporating Fe into protoporphyrin IX to form heme. As a result, protoporphyrin accumulates in the peripheral blood, where it can be measured by a simple fluorescence technique. Using a hematofluorometer, Roscoe et al. (1979) reported increased levels of protoporphyrin in a single drop of untreated blood following administration of Pb shot to mallard ducks. Following the administration of 1 to 18 number 4 Pb shot, the blood concentrations of protoporphyrin IX were related to clinical signs of Pb poisoning. Although death corresponded to protoporphyrin IX concentrations >800 μg/dL in penned ducks, lesser concentrations would probably lead to death in the wild. For a study of Pb exposure in two types of pen-reared and wild ducks, toxicity and lethality corresponding to much less elevated blood protoporphyrin IX concentrations (<800 μg/dL) are reported (Rattner et al. 1989).

Sample collection times for a set of biomarker indicators is 0.5-1.0 day for each resource sampling unit for two to three technicians. The estimated laboratory analysis cost for porphyrin measures is $25-$75 a sample.

VARIABILITY: A study of herring gulls from the Great Lakes may serve as an example of the spatial variability of porphyrin measures within a resource sampling unit. Fox et al. (1988) have shown that gulls from contaminated areas have considerably higher concentrations of highly carboxylated porphyrins in liver than gulls from "clean" areas. In the areas studied, the frequency of levels >10 times the median of the control (clean) values ranged from 22 to 100%. The expected temporal variability for porphyrin in animal liver throughout the year was not estimated.

PRIMARY PROBLEMS: Information on species othei than birds will enable further utilization of porphyrins in ecological monitoring programs.

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G.2.7 INDICATOR: Histopathologic Alterations

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: Histopathological alterations are most valuable as an indicator of exposure to a variety of anthropogenic pollutants. Because the alterations occur after physiologic or biochemical perturbation, the responses may be thought of as integration of molecular changes at the cell, tissue, and organism level. This indicator is distinguished from (response) indicators of gross pathology in that its measures are not highly perceptible to the unaided eye. The utility of histopathological alterations as biomarkers is most studied in teleost fish, but changes in tissues and cells occur in all vertebrates and invertebrates, and laboratory studies of histopathological consequences of toxic exposure are well documented. No resource specificity or geographic limitations are apparent.

The techniques used to monitor this indicator are ready for field use. Considerable testing has been completed in the laboratory, but an inadequate application to field studies is the major cause of lack of historical data. The Status and Trends Program (mussel watch) of the U.S. National Oceanographic and Atmospheric Administration (NOAA) and limited monitoring efforts attest to the utility of these approaches.

INDEX PERIOD: Although season-related variation exists, no specific sampling window during the year was proposed.

MEASUREMENTS: Extensive methodology exists for the determination of tissue, cellular and subcellular responses. New plastic embedment procedures improve resolution without appreciably increasing cost. Histopathologic measures demonstrated to be useful as biomarkers include the following.

- **Hepatocellular necrosis and sequelae:** This includes coagulative necrosis associated with exposure to anthropogenic environmental toxicants in both mammals and fish (Wyllie et al. 1980; Meyers and Hendricks 1985; Popper 1988), regenerative hyperplasia indicative of extensive prior necrosis, and bile ductular/ductal hyperplasia, a lesion of chronic duration consistently found in wild fish from impacted sites (May et al. 1987).

- **Spongiosis hepatis:** this results from fibroblastic transformation of Ito cells (Yamamoto et al. 1986) and observed in winter flounder of coastal New England, English sole in Puget Sound, and in fishes collected from impacted sites in the Kanawha River of West Virginia.

- **Hepatocytomegaly:** enlarged hepatocytes seen as an early change in English sole of Puget Sound, Washington (Myers et al. 1987), in sea pen cultures of Atlantic salmon in Puget Sound (Kent et al. 1988), and in livers of pond-cultured fingerling striped bass (Groff 1989), or as a rare form of chronic swelling of endoplasmic reticulum cisternae encountered in high prevalence in winter flounder of Boston Harbor and nearby estuaries (Murchelano and Wolke 1985).

- **Foci of staining alteration:** an early stage in the spectrum of lesions seen between normal and tumor-bearing liver that have been associated with eventual tumor formation (Hendricks et al. 1984).

- **Liver neoplastic lesions:** examples are hepatic adenoma, hepatocellular carcinoma, cholangioma, and cholangiocarcinoma.

Although somewhat subjective, user-oriented computer software for the quantification of lesions exists. When applied to characterize magnitude of response, data amenable to statistical evaluation are obtainable. Sample collection times for a set of biomarker indicators is 0.5-1.0 day for each resource sampling unit for two to three technicians. The estimated laboratory analysis cost for histopathologic measures is $50-$100 a sample.

VARIABILITY: Responses are easily recognized provided that proper reference and control data are available. Physiologic and sex-related variation exists and must be taken into account, but should not prevent the immediate application of histopathologic biomarkers because normal variation is at cell and subcellular level of organization, whereas effective biomarkers involve tissue components. The expected spatial variability of hispathologic alterations within a resource sampling unit and the expected temporal variability of these alterations during the index period were not estimated.

PRIMARY PROBLEMS: An experienced histologist is required for proper interpretations of slides.

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G.2.8 INDICATOR: Macrophage Phagocytotic Activity

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: The immune system, in its capacity to destroy foreign material and protect the host against disease, can serve as a useful sentinel of the health status of environmentally stressed organisms. Several responses have been used as measures of immune function and status, including lymphocyte mitogenesis (Laudenslager et al. 1983; Spitsbergen et al. 1986), antibody-producing cell formation (Anderson et al. 1983), antibody production (O'Neill 1981), and nonspecific macrophage activity (Weeks et al. 1986, 1987, 1988; Weeks and Warinner 1984; Wishovsky et al. 1990). These and other elements of the immune system have been shown to be affected (depressed or stimulated) by exposure to toxicants. The nonspecific macrophage activity assays have been extensively field tested, primarily in fish, and are suited to a screening-level evaluation of an important component of the immune system.

This indicator has been tested in fish specimens obtained from contaminated and uncontaminated estuarine waters and in experimentally exposed animals; it is considered ready for regional evaluation.

INDEX PERIOD: Although field experience with this assay has been limited to fish specimens sampled during the late spring through autumn months (these fish species are unavailable during the winter months), the assay method is believed to be applicable during all seasons.

MEASUREMENTS: Macrophage activity is evaluated by isolating macrophages and measuring either directly by microscopically observing the active uptake of foreign particulate matter (phagocytosis), or indirectly by measuring the chemiluminescence resulting from the production of reactive oxygen intermediates that accompanies macrophage ingestion of foreign matter. The macrophage phagocytosis assay measures the percentage of macrophages capable of ingesting formalin-killed *Escherichia coli* during an incubation period of 90-120 min at 15°C. The macrophage suspension is washed and placed on microscope slides, which are differentially stained and examined under oil immersion microscopy. It is easily and inexpensively carried out, requiring only standard laboratory equipment and techniques. In the chemiluminescence assay, macrophages are stimulated by using soluble (phorbol myristate acetate) or particulate (zymosan or bacteria) stimuli in the presence of luminol, which enhances the emitted luminescence. Photon emission is measured with a liquid scintillation counter or luminometer. The procedure is rapid (30-60 min), inexpensive, and easily performed.

Sample collection time for a set of biomarker indicators is 0.5-1.0 day for each resource sampling unit for two to three technicians. The estimated laboratory analysis cost for phagocytotic activity measures is $25-$75 per sample.

VARIABILITY: The variability of phagocytotic activity among replicates from fish populations maintained in the laboratory has been minimal (approximate coefficient of variation was 25-30%). The expected spatial variability of phagocytotic activity within a resource sampling unit and its expected temporal variability throughout the year were not estimated.

PRIMARY PROBLEMS: Despite the considerable similarity in immune system functions across species, some development work is necessary to test and validate these assays for invertebrates and for mammals. Further research is needed to develop more quantitative relationships that may permit this assay to be considered a biomarker of potential adverse effects. To increase this biomarker's utility for diagnosing chemically induced disfunction of the immune system component, laboratory studies of fish exposed to selected contaminants should be performed to evaluate the immumodulatory effects of individual aquatic contaminants.

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G.2.9 INDICATOR: Blood Chemistry

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: Blood chemistry assays basically evaluate performance of an animal's organ systems *in vivo*. Direct assessment of organ function is sometimes useful when other tests are ineffectual or cannot be performed. Circulating concentrations of biochemicals associated with the General Adaptation Syndrome are a function of their secretion into and clearance from the blood. Even though these indicators are representative of physiological functions in the organism, most are biochemical in nature and could serve in a restricted sense as screening indicators of exposure. Lag time between exposure to stress and biochemical response is typically short (within minutes to hours), and the response may persist for some time (days to months) following exposure.

Blood chemistry assays are simple to administer, objective, and in many cases interpretable. Many of these types of measurements have been taken on a wide variety of fish under a variety of environmental conditions and are basically ready for use in field situations. The underlying physiological bases for measurable changes are usually understood and can be traced in many instances to specific tissue and organ dysfunctions. For many of the cell/tissue/organ dysfunction indicators, however, use in routine monitoring is recommended provided that they are used in conjunction with other bioindicators at higher levels of biological organization (e.g., histopathological or bioenergetic parameters, growth) until the link between blood chemistry and organ dysfunction is better understood (see also Indicator G.2.4, "Cholinesterase Levels").

INDEX PERIOD: No index period is known to have minimal temporal variability. Although season may affect the absolute values of some parameters, comparisons can be made between animal data collected within the same season.

MEASUREMENTS: Indicators of cell/tissue/organ dysfunction represent a wide variety of assays including (1) serum enzymes (i.e., lysosomal enzymes, transaminases), (2) electrolyte homeostasis (e.g., Na^{2+}, K^{+}), (3) carbohydrate and lipid metabolism (glucose, triglycerides), (4) endocrine-related hormones (i.e., corticosteriods, catecholamines), and (5) reproductive hormones (i.e., estradiol, testosterone). These five groups of circulating chemicals represent myriad physiological processes and functions in the organism, and most groups should be chosen as indicators with care relative to the species, environmental conditions, state of development, and sex of the organism which is being monitored.

Because many of these variables are biochemical level indicators, they are short-lived in the blood and should be measured at discrete time periods of short intervals. Sample collection times for a set of biomarker indicators is 0.5-1.0 day per resource sampling unit for two to three technicians. The estimated laboratory analysis cost for blood chemistry is $25 per sample.

VARIABILITY: Because of the short-lived nature of chemicals in the blood, the sample variability for most of these chemical parameters is relatively high. The independent variables which can influence the timing and magnitude of these variables in the blood are size, sex, age, and state of development of the organism and environmental factors such as season, temperature, food availability, habitat availability, and population density. Much information exists in the literature relative to the variability of many circulating blood parameters, particularly the more common commercial and sport species of fish (i.e., salmonids, centrachids) and domesticated animals (e.g., cattle, sheep, horses). The expected spatial variability of blood chemistry measures within a resource sampling unit and their temporal variability throughout the year were not estimated.

PRIMARY PROBLEMS: One major constraint is that normal or reference values for most species have not been statistically established for field situations. Before these types of measures serve as early warning signals of impending effects at the organism, population, or community level, some research is needed to establish the relationship between these types of assays and responses observed at higher levels of biological organization.

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G.2.10 INDICATOR: Cytochrome P-450 Monooxygenase System

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: The cytochrome P-450 monooxygenase system is most valuable as a screening indicator of exposure to a variety of petroleum hydrocarbons (particularly polycyclic aromatic hydrocarbons [PAHs]) and halogenated hydrocarbons (dioxins, polychlorinated biphenyls [PCBs], PBBs). In some cases such as PAHs, it may be viewed as a diagnostic indicator because monooxygenase activity is required for activation to ultimate carcinogens. Lag time between exposure and response is typically short (within hours). Response generally persists throughout exposure and for some time thereafter (days to weeks), but method selection is important here (see Measurements). Its utility as a biomarker is most studied in teleost fish, but inductions of the system apparently occur in all vertebrates. No resource specificity or geographic limitations exist.

This technique is ready for field testing; in fact, considerable field testing has occurred in the case of petroleum-related contamination of aquatic systems with encouraging results. Considerable basic and applied research, however, is required for this approach to reach its potential as a biomarker for routine regional monitoring.

INDEX PERIOD: As with biochemical indicators in general, monooxygenase responses can be measured at discrete points in time. No temporal constraints are known, although active reproductive status may reduce baseline enzyme activity and/or the induction response to contaminants.

MEASUREMENTS: Several approaches are available; see Payne et al. (1987) and Stegeman and Kloepper-Sams (1987) and references therein. Simplest and least expensive, and often most sensitive, are associated enzyme activities such as ethoxyresorufin O-deethylase and aryl hydrocarbon hydroxlyase; these are measured spectrophotometrically, typically on microsomal fractions of hepatic or other (kidney, gut, heart, gill) tissues that are obtained by ultracentrifugation. However, chronic exposures sometimes can result in loss of activity following inductions. Considerably more involved, but quite powerful, techniques involve immunochemical assays for specific cytochrome P-450 isozymes and CDNA probes for messenger RNAs for specific isozymes. These have indicated inductions following losses of catalytic activity (as indicated by the enzyme assays mentioned earlier). Additionally, the greater specificity of these latter approaches can provide clues concerning the chemical compounds underlying an observed induction.

Most techniques available merit adaptations to make them simpler and more available for routine biomonitoring. Sample collection times for a set of biomarker indicators is 0.5-1.0 day per resource sampling unit for two to three technicians. The estimated laboratory analysis cost for enzyme analysis is $25-$75 per sample. Test responses are quite sensitive to petroleum hydrocarbons and changes are relatively easy to discern provided proper reference or baseline data are available.

VARIABILITY: The expected spatial variability of this indicator within a resource sampling unit and its temporal variability throughout the year were not estimated.

PRIMARY PROBLEMS: The types of compounds these responses are useful for appear to be somewhat limited, particularly in fish, but considerable species (across vertebrate taxa) variation occurs, and research in this area is needed. It is also important to note that some compounds (some solvents and metals) can inhibit these responses and could lead to "false negatives" in cases where inducers co-occur with such inhibitors. A constraint here is the lack of adequate historical data for establishing baseline values for most species of potential interest. Considerable research is needed in the area of chemical interactions before this technique is relied upon in situations evaluating highly complex mixtures.

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G.2.11 INDICATOR: Enzyme-Altered Foci

CATEGORY: Exposure and Habitat/ Biomarkers

STATUS: Research

APPLICATION: Enzyme-altered foci (EAF) refer to the appearance of hepatocytes (identifed by histochemical changes) that are an early stage in a spectrum of lesions in the progressive development of neoplasia. With histochemical procedures to localize selected enzymes, altered phenotypes of "carcinogen-initiated" cells are demonstrated. EAF are most valuable as an indicator of prior exposure of the host to one of a variety of chemical carcinogens. First described in rodent liver, EAF have been shown to increase in a dose-dependent fashion with application of compounds to promote liver tumors (Pitot 1988; Hinton et al. 1988; Hendricks et al. 1984; Nakazawa et al. 1985). Lag time between exposure and effect is likely to be weeks in duration. Because growth of foci occurs with application of promoters, focal volume may indicate both initiation and promotion. Care in method selection is important because negative and positive markers exist (Peraino et al. 1983).

This technique is ready for field testing, although developmental research (species specific) is required to bring this approach to its full potential as a biomarker for routine regional monitoring.

INDEX PERIOD: No optimal sampling window was recommended; however, no apparent temporal constraints exist.

MEASUREMENTS: Field samples can be quenched in liquid N and stored indefinitely. Processing includes routine cryostat sectioning of frozen tissue (livers of large fish) or freeze- drying and embedment in glycol methacrylate using nonexothermic polymerization steps (small fish or early life forms). With the latter processing, nine enzyme reactions (Hinton and Lauren 1989) have been proven useful. Several approaches are available (see Pretlow et al. 1987; Peraino et al. 1983).

VARIABILITY: The spatial and temporal variability needs to be assessed in various species of feral fish. The expected spatial variability of this indicator within a resource sampling unit and its temporal variability throughout the year were not estimated, because no proper reference or baseline data are available.

PRIMARY PROBLEMS: The constraints to field implementation is the lack of adequate historical data for establishing baseline values and no prior field application. Increasing volume of foci and appearance of enzyme-altered nodules may signify incipient promotion of carcinogen-initiated tissue.

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APPENDIX G.3: INDICATOR FACT SHEETS FOR LANDSCAPE AND HABITAT INDICATORS

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G.3.2 INDICATOR: Linear Classification and Physical Structure of Habitat

CATEGORY: Exposure and Habitat/ Habitat

STATUS: High-Priority Research

APPLICATION: The structure of animal habitats in many terrestrial and in some wetland communities can be considered to consist of vertical layers and a horizontal distribution of habitat variables within each layer. The Habitat Linear Classification System (HLCS; Short 1990) is a simple way to translate the vertical and horizontal dimensions of habitats into a numeric whose status and trends can be compared between sites or regions. The HLCS can be applied to different types and resolutions of monitoring data, such as satellite imagery and aerial photography (both with ground-truthing) and field surveys. Like the HLCS, The Habitat Layers Index (HLI; Short and Williamson 1986) can be calculated from data at several spatial scales, and together these indices provide a way to evaluate and monitor habitat structure and predict potential animal diversity from that structure.

Application of the HLCS to field survey data from south central Colorado indicated that the algorithm provides values that are linear as the number of clumped cells within the grid is increased, that an interpretable distinction could be made between n-cells that were clumped or dispersed within a grid, and that signatures from different habitats varied in a way that seemed related to the way animal species used those habitats.

It is important to have a habitat indicator that can measure fundamental land-use changes in agroecosystems and forests and reflect plant succession, urbanization, desertification, etc., because these changes impact wild animals. Use of the HLCS will allow EMAP to characterize the effects of changing habitat on animals at a regional and national scale.

INDEX PERIOD: Field surveys to measure habitat variables for the HLCS should be conducted when vegetation is in full leaf.

MEASUREMENTS: To calculate the HLCS, map-based data are overlaid on a grid, or field survey data are collected from a gridded sampling unit. While only habitat layers are distinguished from remotely sensed data, a variety of habitat variables are distinguished from field surveys. Two metrics are developed for data about layers and variables: (1) the proportion of grid cells that contain a particular habitat layer or important habitat variable; and (2) the proportion of grid-cell perimeter segments that surround occupied cells. The HLCS will be most useful if field surveys in all terrestrial and suitable wetland resource classes are standardized, have a consistent format, and measure for the same variables. Variables include habitat layers, surface cover, and a variety of vegetative variables in surface, midstory and overstory layers. The product of the analysis is a series of linear traits describing the individual habitat variables or layers within the grid. This series provides a "signature" that is descriptive of the habitat, and it is this signature that whose status and trends can be compared among sites.

The analysis of habitat structure to implement the HLCS would cost approximately $500-$1000 for each resource sampling unit, the amount depending on habitat complexity. The recommended interannual sampling frequency is 5 years.

VARIABILITY: The expected spatial and temporal variabilities within a resource sampling unit and during the index period, respectively, were not established.

PRIMARY PROBLEMS: Research is needed to determine a best size for a survey grid and survey grid cells and the most efficient and cost-effective method to sample habitat variables.

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G.3.3 INDICATOR: Habitat Proportions (Cover Types)

CATEGORY: Exposure and Habitat/ Landscape

STATUS: High-Priority Research

APPLICATION: Mapping and determining proportions (P_i) of various land use or vegetation cover types in a landscape is a basic measurement when considering both extent and change in vegetation and associated animal composition and diversity (Noss 1983). In addition, land use is an important factor in determining the type and amount of nonpoint-source pollutants entering inland and coastal waters.

Habitat proportions should be valuable for monitoring purposes because of the extensive development of P_i as a landscape property permitting application of percolation theory (Gardner et al. 1987). If habitat is randomly scattered on the landscape, then $P_i = 0.59$ represents a "percolating" habitat. Above this value of P_i, the habitat tends to be connected throughout the landscape, permitting animal populations to move across the entire available habitat and fully utilize the resource. If P_i is less than 0.59, then the habitat is disconnected and isolated into patches that make it much less available to animals (O'Neill et al. 1988). If, however, the habitat of concern is susceptible to disturbances such as fire, large values of P_i permit the disturbance to propagate throughout the landscape (Turner et al. 1989). If the assumption of random distribution of the habitat is relaxed, then percolation theory becomes more useful as an indicator for real landscapes.

Near-Coastal and Inland Waters: Proportions of land use have consistently explained variation in water chemistry for large geographic areas, especially for sediments and nutrients (Omernik 1977; Hunsaker 1986; Osborne and Wiley 1988). This relationship exists because of the biogeochemical cycling that links terrestrial and aquatic systems and is dominated by nonpoint-source pollution in surface runoff from disturbed areas.

Forests: Monitoring the distribution of tree species is important for assessing the total extent and rate of change in extent of different forest types. Distribution patterns of vegetation result from interactions between natural and human altered climatic, terrestrial, and biological habitat conditions (Braun 1950; Daubenmire 1947; Walter 1973). Patterns of vegetation are thus in response to environmental conditions. Changes in conditions, either from natural (e.g., succession) or human-induced (e.g., timber harvest) influences can affect or stress the ecosystem and can alter the distribution patterns.

Monitoring the vegetative and physical structure of ecosystems is important because changes in structure may result in loss of desirable vegetation components (e.g., species, life forms, communities) or in acute cases, alteration of ecosystem function. An example of the latter case occurs in the northern forested region of the upper Midwest where historic logging, followed by extensive fires, entirely altered the forest vegetation, the forest floor litter, and the associated surface water chemistry. Additionally, structural diversity has generally been shown to have a positive relationship with animal and plant species diversity (Short and Williamson 1986).

INDEX PERIOD: The optimal sampling window for remotely sensed data from which habitat proportions are calculated is the growing season. An optimal measurement window for field surveys in all terrestrial resource classes is when perennial vegetation is in leaf-out condition; for arid lands, late spring to early summer is optimal. For remote sensing images, a high sun angle is good to reduce topographically induced illumination differences.

MEASUREMENT: Land use and land cover data can be classified from remotely sensed data, and the area of each type can be determined. If the images are in digital form, areal measures can be calculated by computer. The land use and vegetation cover data to calculate this indicator would be provided primarily by EMAP-Characterization and augmented by field survey data such as the USDA Forest Service FIA and FPM inventories. Standard digital image processing techniques would be employed, involving image-to-image registration and change detection procedures coupled with spectral classifications (Pilon et al. 1988). The recommended interannual measurement frequency is 5 to 10 years. The development of classifications for relevance to animal indicators is more difficult. Animal species can be associated with different vegetation types to estimate faunal composition, diversity, and relative abundances in sampling units. Such relationships will likely require field data collection to verify habitat classifications, but this work could be done when the animal data are being collected.

VARIABILITY: Because the remotely sensed data will provide 100% spatial coverage in the landscape sampling units, the expected spatial variability of habitat proportions within a resource sampling unit is inconsequential. The temporal variability of habitat proportions during the index period will produce extreme values that deviate <10% of the sample mean.

PRIMARY PROBLEMS: Ground-truthing and correspondence with selected animal indicators will require significant effort.

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Turner, M.G., R.H. Gardner, V.H. Dale, and R.V. O'Neill. 1989. Predicting the spread of disturbance in heterogeneous landscapes. Oikos 55:121-129.

Walter, H. 1973. Vegetation of the Earth. Springer-Verlag, New York.

G.3.4 INDICATOR: Patch Size and Perimeter-to-Area Ratio

CATEGORY: Exposure and Habitat/ Landscape

STATUS: High Priority Research

APPLICATION: Patch dynamics have implications for movements of biota, nutrient cycling, and energy flux. Studies in many different ecosystems have demonstrated that a number of spatially related habitat attributes or landscape indices are related to animal diversity and abundance. This indicator will provide an index of terrestrial biotic integrity which can provide a measure of population viability, and will provide critical information which can be used for analysis and assessment of migratory patterns. Patch size is a critical consideration especially when connectivity between patches is poor. Many habitat patches in fragmented landscapes are too small to support viable populations, or even a single home range or territory of certain large mammal or bird species. The distribution of suitable habitat among patches of various size is just as important for animals as the total area of suitable habitat in a landscape.

Patch perimeter to area (edge to interior) ratio is a measure of habitat fragmentation. It is useful for forests, where the amount of forest edge relative to forest interior is known to be an important determinant of vertebrate community structure and population viability of forest interior species. The relationship is best documented for birds, where artificial edge favors "weedy" species over native species and increases rates of nest predation and cowbird parasitism on many forest species. Numerous studies have documented the deterioration of bird populations in landscapes with high edge-interior ratios, yet this variable has seldom been measured directly. For wetlands, the significance of shape in a monitoring context is in its relationship to loss of acreage and function over time.

The frequency of patches in various size categories would be plotted for each habitat type. This distribution could be compared with home range sizes or minimum areas required for population persistence for native vertebrates. The fractal dimension of patches is a measure of perimeter to area ratio and quantifies the dissectedness of boundaries (O'Neill et al. 1988); this indicator is discussed separately (see Indicator G.3.5, "Fractal Dimension").

INDEX PERIOD: The optimal sampling window for remotely sensed data from which patch size and perimeter to area ratio are calculated is the growing season.

MEASUREMENTS: Measurements of patch areas and perimeters are relatively straightforward in many landscapes. They can be done manually on an aerial photo; for large areas, however, the use of a Geographic Information System and digital data are necessary. The land-use and vegetation-cover data to calculate these indices would be provided by EMAP-Characterization. The recommended interannual sampling frequency is 5 to 10 years.

VARIABILITY: Because the remotely sensed data will provide 100% spatial coverage in the sampling units, the expected spatial variabilities of patch size and perimeter to area ratios are inconsequential. The temporal variabilities of patch size and perimeter to area ratios during the index period will produce extreme values that deviate <10% of the sample mean.

PRIMARY PROBLEMS: No significant problems are anticipated.

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Wilcove, D.S., C.H. McLellan, and A.P. Dobson. 1986. Habitat fragmentation in the temperate zone. Pages 237-256. In: M.E. Soule, ed. Conservation Biology: The Science of Scarcity and Diversity. Sinauer, Sunderland, MA.

G.3.5 INDICATOR: Fractal Dimension

CATEGORY: Exposure and Habitat/ Landscape

STATUS: High-Priority Research

APPLICATION: The fractal dimension, F, is a measure of the fractal geometry (Mandelbrot 1983) and an index of the complexity of shapes on the landscape. If the landscape is composed of simple geometric shapes like squares and rectangles, the fractal dimension will be small, approaching 1.0. If the landscape contains many patches with complex and convoluted shapes, the fractal dimension will be large (Krummel et al. 1987). F is calculated from maps of land use or vegetation cover and appears to be useful for characterizing landscape pattern (Krummel et al. 1987, O'Neill et al. 1988).

INDEX PERIOD: The optimal sampling window for remotely sensed data from which fractal dimensions are calculated is the period that best allows one to discriminate the habitat patterns of interest.

MEASUREMENTS: The fractal dimension is estimated by regressing the logarithm of polygon perimeter (dependent variable) against the logarithm of area (independent variable) for all patches on a digitized map. The fractal dimension is related to the slope of the regression, *S*, by the relationship (Lovejoy 1982):

$$F = 2S$$

The land-use and vegetation-cover data to calculate these indices would be provided by EMAP-Characterization. The recommended interannual sampling frequency is 5 to 10 years.

O'Neill et al. (1988) analyzed the fractal dimension for 58 quadrangles in the eastern United States. This study quantified the regional variability of this indicator by using data with a spatial resolution of 200 m. The fractal dimension ranged from 1.24 to 1.45 with a coefficient of variation of 0.04. These values are believed to be fairly representative of landscapes in North America; however, this needs to be verified for the western United States.

VARIABILITY: Because the remotely sensed data will provide 100% spatial coverage in the landscape sampling units, the expected spatial variability of the fractal dimension within resource sampling units are inconsequential. The temporal variability of fractal dimension during the index period was not estimated.

PRIMARY PROBLEMS: The fractal dimension, as with some other landscape indices, is probably not a good indicator for a single measurement in time because we lack currently knowledge of how this parameter relates to ecosystem function. However, as an indicator of landscape pattern change over large geographic areas it should be powerful. Also, this indicator is probably most useful when used together with other landscape indices such as contagion and proportion of land use.

REFERENCES:

Krummel, J.R., R.H. Cardiner, G.Sugihara, R.V. O'Neill, and P.R. Coleman. 1987. Landscape pattern in a disturbed environment. Oikos 48:321-324.

Lovejoy, S. 1982. Area-perimeter relation for rain and cloud areas. Science 216:185-187.

Mandelbrot, B. 1983. The Fractal Geometry of Nature. W.H. Freeman and Co., New York.

O'Neill, R.V., J.R. Krummel, R.H. Gardner, G. Sugihara, B. Jackson, D.L. DeAngelis, B.T. Milne, M.G. Turner, B. Zygmunt, S.W. Christensen, V.H Dale, and R.L. Graham. 1988. Indices of landscape pattern. Landscape Ecol. 1:153-162.

G.3.6 INDICATOR: Contagion or Habitat Patchiness

CATEGORY: Exposure and Habitat/ Landscape

STATUS: High-Priority Research

APPLICATION: The horizontal heterogeneity or patchiness of a habitat is a primary determinant of animal diversity and abundance. Up to a certain threshold, increases in heterogeneity correspond to increased diversity of species, resources, and abundances of animals dependent on those resources. Patchiness is caused by resource heterogeneity (e.g., sinkholes, seeps, outcrops, unusual soils) and by disturbances (e.g., treefall gaps, spot fires, insects).

Contagion is a landscape index derived from information theory (Shannon and Weaver 1962) as applied to landscape pattern (O'Neill et al 1988). Contagion measures the extent to which land uses are aggregated or clumped:

$$C = 2n \ln n + \cdot_i \cdot_j P_{ij} \ln P_{ij}$$

where P_{ij} is the probability that a grid point of land use *i* will be found adjacent to a grid point of land use *j*. The term *2n* ln *n* represents a maximum in which all adjacency probabilities are equal; that is, for a randomly chosen spot on the landscape, there is an equal probability that any land use type is adjacent to the chosen point. At high values of C, the landscape tends to be composed of large, contiguous patches. At low values, the landscape is dissected into many small patches.

The index C used by O'Neill et al. (1988) retains a sensitivity to the number of land-use types that is avoided by using the recommended formulation:

$$C = \cdot_i \cdot_j P_{ij} \ln P_{ij} / 2n \ln n$$

Their study analyzed contagion for 94 quadrangles in the eastern United States, and quantified the regional variability of this indicator by using data with a spatial resolution of 200 m. The contagion values ranged from 9.5 to 22.8 with a coefficient of variation of 0.16, and are believed to be fairly representative of landscapes in North America; however, this needs to be verified in the western United States.

INDEX PERIOD: The optimal sampling window for landscape data from which contagion is calculated is the growing season.

MEASUREMENTS: The land-use and vegetation-cover data to calculate this indicator would be provided by EMAP-Characterization. The recommended interannual measurement frequency is 4 to 5 years. At the landscape scale, contagion is a measure of patchiness.

Several measures of habitat patchiness for small geographic areas have been proposed. Roth (1976) used the coefficient of variation (CV) of distance to nearest trees and shrubs in point-quarter samples, and found that bird richness and abundance increased in more heterogeneous areas. Noss (1988) tested several measures of habitat patchiness in a Florida hardwood forest, including CV of distances to nearest trees, nearest shrubs, and both combined; CV of shrub density; CV of canopy openness, diversity of tree species, shrub species, and both combined; and proportion of plot area in canopy gaps, bayheads (dense broadleaf evergreen vegetation in seepage areas), and both combined. The best predictor of bird abundance was proportion of area in canopy gaps and bayheads combined. Species richness was significantly related only to variation in shrub density. Mapping these patches on sample plots through field surveys is straightforward, though time-consuming (but less time-consuming than using point-quarter samples). Current aerial photos, when ground-truthed, may be more useful.

VARIABILITY: Because the remotely sensed data will provide 100% spatial coverage within the landscape sampling units, the expected spatial variability of contagion or habitat patchiness within resource sampling units is inconsequential. The temporal variability during the index period was not estimated.

PRIMARY PROBLEMS: Some measures of habitat patchiness require detailed field surveys. However, direct measurement of patchiness for EMAP will be calculated from the program's landscape characterization data.

REFERENCES:

Noss, R.F. 1988. Effects of edge and internal patchiness on habitat use by birds in a Florida hardwood forest. Ph.D. dissertation. University of Florida, Gainesville.

O'Neill, R.V., J.R. Krummel, R.H. Gardner, G. Sugihara, B. Jackson, D.L. DeAngelis, B.T. Milne, M.G. Turner, B. Zygmunt, S.W. Christensen, V.H. Dale, and R.L. Graham. 1988. Indices of landscape pattern. Landscape Ecol. 1:153-162.

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G.3.7 INDICATOR: Gamma Index of Network Connectivity

CATEGORY: Exposure and Habitat/ Landscape

STATUS: Research

APPLICATION: The connectivity of habitat in a landscape is a measure of how easily individuals of a given animal species can travel about, which in turn is important to meeting daily and seasonal life history needs, allowing juvenile dispersal, escaping disturbance, and providing for gene flow. While in theory the usefulness of such as index appears logical, the data are lacking to support the application of this index to a specific species.

INDEX PERIOD: No optimal sampling window exists for remotely sensed data from which gamma indices are calculated.

MEASUREMENTS: The gamma index of network connectivity is the ratio of links in a network to the maximum possible number of links in that network. The formula is $y = L/Lmax = L/3(V - 2)$, where L is the number of links (i.e., corridors), $Lmax$ is the maximum possible number of links, and V is the number of nodes (i.e., habitat patches; Forman and Godron 1986). The recommended interannual sampling frequency is 4 to 5 years.

VARIABILITY: Because the remotely sensed data will provide 100% spatial coverage in the landscape sampling units, the expected spatial variability of the gamma index within resource sampling units is inconsequential. The temporal variability of the Gamma index during the index period was not estimated.

PRIMARY PROBLEMS: This is a simple measure, but its ecological relevance is unknown. Connectivity in real landscapes would depend on habitat structure within corridors, the nature of surrounding habitat (matrix), corridor width:length ratio, and details of the autecology of species expected to use the corridor.

REFERENCE:

Forman, R.T.T., and M. Godron. 1986. Landscape Ecology. John Wiley and Sons, New York.

BIBLIOGRAPHY:

Noss, R.F. 1987. Corridors in real landscapes: A reply to Simberloff and Cox. Conserv. Biol. 1:159-164.

G.3.8 INDICATOR: Patton's Diversity Index

CATEGORY: Exposure and Habitat/ Landscape

STATUS: Research

APPLICATION: Patton's diversity index (DI) is actually a measure of the amount of edge within an area of a given size (thus, it is a measure of habitat diversity). The amount of artificial edge in a landscape is a good index (inverse) of terrestrial biotic integrity, even though wildlife managers traditionally have considered edge to be beneficial because many game species are edge-adapted. A landscape is "less natural" the larger the amount of artificial edge.

INDEX PERIOD: The optimal sampling window for landscape data from which Patton's diversity index is calculated is the growing season.

MEASUREMENTS: This index is based on measurements from aerial photos. The land use and vegetation cover data to calculate these indices would be provided by the EMAP-Characterization. The formula is $DI = TP/2A$ (Patton 1975), where TP is the total perimeter of an area plus any linear edge within the area, and A is the total area. Thomas et al. (1979) split Patton's index into two indices, one each for inherent edge (the natural boundary between two plant communities) and induced edge (a boundary caused by disturbance, human or otherwise). Other considerations suggest separating edge into natural (created by either natural gradients or disturbances) and artificial (created by human land-use), because the latter tends to be longer-lasting and often associated with continuing human impact. Edges may also be classified on the basis of contrast between the two habitats. The recommended interannual sampling frequency is 5 to 10 years.

VARIABILITY: Because the remotely sensed data will provide 100% spatial coverage in the landscape sampling units, the expected spatial variability of this index within a resource sampling unit is inconsequential. The temporal variability of Patton's DI during the index period was not estimated.

PRIMARY PROBLEMS: Thomas et al. (1979) comment that Patton's DI assumes that the total perimeter of an area is actually edge, whereas this is usually not true in an ecological sense. However, it would be simple to focus only on true edge (and perhaps, only artificially-created edge) simply by not including perimeter of the sample area that abuts similar habitat.

REFERENCES:

Patton, D.R. 1975. A diversity index for quantifying habitat "edge." Wildl. Soc. Bull. 3:171-173.

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APPENDIX H: INDICATOR FACT SHEETS FOR ATMOSPHERIC STRESSORS

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H.1 INDICATOR: Ozone

CATEGORY: Stressor/ Chemical

STATUS: High-Priority Research

APPLICATION: In the atmosphere, chemical emissions from natural and man-made sources are subjected to physical, chemical, and photochemical processes, which may produce transformation products that can be as toxic as or more toxic to ecological resources than the parent chemicals. The atmosphere serves as the conduit from emissions sources to the biosphere. Once chemicals are emitted into the atmosphere, their pathways to receptors in terrestrial and aquatic ecosystems are a function of a variety of factors. Atmospheric residence times depend upon characteristics such as mode and rate of emission, atmospheric transformations, and physical state.

Ozone is regulated by EPA National Ambient Air Quality Standards and is considered both a health and welfare risk. Its degree of ecological impact depends on the deposition rate, toxicity, environmental fate of the pollutant, and organism sensitivity. Deposition of and exposure to ozone affects vegetation through disruption of physiological processes. Ozone is recognized as a major problem in both human health and welfare (U.S. EPA 1986; U.S. EPA 1988a, 1988b).

Lefohn and Moser (1989) focused on methods available for summarizing the hourly average ozone concentration information in biologically meaningful terms. Exposure indices, such as the summation of hourly average concentration equal to or greater than selected thresholds, the number of hourly average concentrations equal to or greater than a selected threshold, and the cumulative index based on a sigmoid weighing function, were described as alternative measures of vegetation exposure to ozone.

INDEX PERIOD: Ozone concentrations would be monitored continuously throughout the year at all EMAP deposition monitoring sites. Currently, ozone concentrations are monitored continuously for specific months of the year and are summarized as hourly average concentrations. According to the geographic region of the United States, ozone is currently monitored for as few as 5 months to as many as 12 months (see Table H-1).

MEASUREMENTS: Peak ozone exposures would be measured; data will be reported as peak values, seasonal and annual averages. Currently, ozone measurements (in ppmv) can be obtained from data bases of existing monitoring networks (e.g., EPA Atmospheric Information Retrieval System [AIRS], National Park Service, Mountain Cloud Chemistry Program, and EPA National Dry Deposition Network). Measurement error is expected to produce ranges that deviate 20% from the true value.

VARIABILITY: The expected spatial variability of ozone concentrations within a landscape sampling unit would produce extreme measures that deviate <20% from the mean value. The expected temporal variability of ozone concentrations during the year could produce measures that deviate as much as 100% from the mean value, the variability depending upon release from emitters and seasonal climatic patterns.

PRIMARY PROBLEMS: (1) Sites monitored in existing atmospheric sampling networks are geographically clumped, usually in association with urban centers. There are few data available from which to judge changes in pollutant concentration over distance from these urban centers. Of the 1384 ozone sites in the EPA AIRS data base, only 33% have been designated as rural or remote. The National Park Service does monitor ozone at several locations around the United States; however, ozone data for only 1983 and 1985 are available. Quality control confirmations have not been completed on data collected between 1986 and 1988. In future years, ozone data may be available from select statewide research networks (e.g., California).

Table H-1. Ozone Monitoring Season by State (Source: 40 CFR Part 58, Appendix D).

State	Begin	End	State	Begin	End
Alabama	March	November	Missouri	April	October
Alaska	April	October	Montana	June	September
Arizona	January	December	Nebraska	April	October
Arkansas	March	November	Nevada	January	December
California	January	December	New Hampshire	April	October
Colorado	March	September	New Jersey	April	October
Connecticut	April	October	New Mexico	January	December
Delaware	April	October	New York	April	October
D.C.	April	October	North Carolina	April	October
Florida	January	December	North Dakota	May	September
Georgia	March	November	Ohio	April	October
Hawaii	January	December	Oklahoma	March	November
Idaho	April	October	Oregon	April	October
Illinois	April	October	Pennsylvania	April	October
Indiana	April	October	Rhode Island	April	October
Iowa	April	October	South Carolina	April	October
Kansas	April	October	South Dakota	June	September
Kentucky	April	October	Tennessee	April	October
Louisiana	January	December	Utah	May	September
Maine	April	October	Vermont	April	October
Maryland	April	October	Virginia	April	October
Massachusetts	April	October	Washington	April	October
Michigan	April	October	West Virginia	April	October
Minnesota	April	October	Wisconsin	April	October
Mississippi	March	November	Wyoming	April	October

(2) Because annual ozone levels are closely linked with meteorological factors, it will be difficult to ascertain the existence of a long-term directional trend in ozone exposures (U.S. EPA 1989).

(3) Until ozone effects research on trees can provide insight on exposure dynamics (e.g., the relative importance of high ozone concentrations versus low concentrations), it will be difficult to identify and defend any one specific ozone exposure parameter. However, on the basis of published results from agricultural research, higher ozone concentrations should be more heavily weighted than lower concentrations. Exposure periods that contain high hourly average concentrations over short periods of time should provide different responses from exposure periods that contain low hourly average concentrations over long periods of time. According to EPA (U.S. EPA 1988a; 1988b), the use of long-term average concentrations should be discouraged. Lefohn and Moser (1989) present a lucid discussion on the subject of selecting an exposure index.

REFERENCES:

Lefohn, A.S., and T. Moser. 1989. Exposure indicators for monitoring air quality in the environment. Prepared for the Environmental Monitoring and Assessment Program (EMAP) of the U.S. Environmental Protection Agency. A.S.L. and Associates, Helena, MT.

U.S. EPA. 1986. Air quality criteria for ozone and other photochemical oxidants. Volume III. EPA 600/8-84/020cF. U.S. Environmental Protection Agency, Environmental Criteria and Assessment Office, Research Triangle Park, NC.

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U.S. EPA. 1988b. Review of the National Ambient Air Quality Standards for ozone: Assessment of scientific and technical information. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

U.S. EPA. 1989. National air quality and emissions trends report, 1987. EPA 450/4-89/001. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

H.2 INDICATOR: Sulfur Dioxide

CATEGORY: Stressor/ Chemical

STATUS: High-Priority Research

APPLICATION: In the atmosphere, chemical emissions from natural and man-made sources are subjected to physical, chemical, and photochemical processes, which may produce transformation products that can be as toxic as or more toxic to ecological resources than the parent chemicals. The atmosphere serves as the conduit from emissions sources to the biosphere. Once chemicals are emitted into the atmosphere, their pathways to receptors in terrestrial and aquatic ecosystems are a function of a variety of factors. Atmospheric residence times depend upon characteristics such as mode and rate of emission, atmospheric transformations, and physical state.

Sulfur dioxide is regulated by EPA National Ambient Air Quality Standards and is considered both a health and welfare risk. The degree of ecological impact depends on the deposition rate, toxicity, environmental fate of the pollutant, and organism sensitivity. Deposition of and exposure to SO_2 has the potential for affecting vegetation through disruption of ecological processes. The major emissions of SO_2 are associated with point sources (U.S. EPA 1989). The pollutant is recognized as both a health and welfare problem. Research investigations near SO_2 point sources have linked foliar injury symptoms in vegetation to gradients of SO_2 exposure (Stratmann 1963).

Exposure indices, such as the summation of hourly average concentrations equal to or above selected thresholds and the number of hourly average concentrations equal to or greater than a selected threshold, are ways to summarize SO_2 information in a potentially biologically useful format. Research results have been published indicating that higher SO_2 concentrations are more important than the lower concentrations in eliciting adverse effects in trees (Stratmann 1963). Therefore, it is possible to design exposure parameters for SO_2 that can be associated with adverse effects. The use of a long-term average concentration for SO_2 should be discouraged (Lefohn and Moser 1989).

INDEX PERIOD: Sulfur dioxide concentrations would be measured continuously throughout the year. For existing long-term monitoring networks, sulfur dioxide is continuously monitored throughout the year in most cases.

MEASUREMENTS: Sulfur dioxide concentrations would be measured on an integrated weekly basis, where a one-week accumulated sample would be collected. Hourly averaged measurements of SO_2 (in ppmv) can be obtained from data bases of existing monitoring networks (e.g., EPA Atmospheric Information Retrieval System [AIRS], National Park Service, and the Mountain Cloud Chemistry Program).

VARIABILITY: The expected spatial variability of SO_2 concentrations within a landscape sampling unit would produce ranges that deviate <20% from the mean value. The expected temporal variability of SO_2 concentrations during the year could produce extreme measures that deviate as high as 100% from the mean value, the variability depending upon release from emitters and seasonal climatic patterns. Sulfur dioxide is more likely to be associated with the emission strength of local point sources than with sources located many miles from a monitor. Thus, a network of higher density is required to adequately quantify SO_2 exposures to vegetation affected by local point sources as opposed to nonpoint, regional sources.

PRIMARY PROBLEMS: (1) Sites monitored in existing atmospheric sampling networks are geographically clumped, usually in association with urban centers. There are few data available from which to judge changes in pollutant concentration relative to distance from these urban centers. Of the 1831 SO_2 sites in the EPA AIRS data base, approximately 33% are designated as rural or remote. The National Park Service does monitor SO_2 at several locations around the United States. However, the SO_2 data are available for

1983 to 1985 only. Quality control confirmations have not been completed on the data collected between 1986 and 1988. Sulfur dioxide is not considered a regional pollutant, and therefore, it is not expected that extensive networks focusing on SO_2 exposures would be introduced in the near future.

REFERENCES:

Lefohn, A.S., and T. Moser. 1989. Exposure indicators for monitoring air quality in the environment. Prepared for the Environmental Monitoring and Assessment Program (EMAP) of the U.S. Environmental Protection Agency. A.S.L. and Associates, Helena, MT.

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U.S. EPA. 1989. National air quality and emissions trends report, 1987. EPA 450/4-89/001. U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

H.3 INDICATOR: Nitric Acid

CATEGORY: Stressor/ Chemical

STATUS: High Priority Research

APPLICATION: Nitric acid is formed in the atmosphere from the reactions of various nitrogen-containing compounds. Once formed, the amount of nitric acid actually deposited on the landscape depends on several factors. For example, a moist receiving surface will retain more nitric acid than one that is dry, and for a given atmospheric condition, complex terrain induces more deposition than one in which less turbulence is generated.

Nitric acid is not now a regulated pollutant but is believed to have potentially major impacts on human health and ecological condition. Both human health and ecological studies are planned or are under way to identify human health and ecological effects and to determine the threshold at which symptoms or changes are apparent. The effects of both peak and chronic exposures will be investigated.

INDEX PERIOD: This indicator would be monitored throughout the year.

MEASUREMENTS: Nitric acid concentrations would be measured by continuously collecting material on a filter surface over a 7-day period (a weekly integrating technique). An accumulation of material on a collection medium over a 24-h period could also be used. Weekly samples would be combined to report monthly, quarterly (seasonal), and annual results.

VARIABILITY: The expected spatial variability of nitric acid within a landscape sampling unit would be similar to that of sulfur dioxide (Indicator H.2); assuming terrain is not complex, ranges should deviate less than 20% from the mean value. The expected temporal variability of nitric acid throughout the year could produce ranges that deviate as much as 100% from the mean, the variability depending on climatological factors and emission releases.

PRIMARY PROBLEMS: Very few sites are presently collecting nitric acid samples on a routine basis. Thus, estimates of spatial variability are unavailable or are unreliable. The sites that are operating are primarily located east of the Mississippi River and in national parks. Sampling procedures sometimes introduce artifacts into the process. The filter pack method measures total nitrogen compounds rather than being specific for nitric acid. Where particulate nitrate is not high, this method offers a reasonable approximation of nitric acid exposure. The annular denuder system has not been successfully tested for sampling periods longer than several days. Field calibration of sampling equipment is not possible at this time. A field device that can accurately introduce nitric acid into either a filter pack or annular denuder has not been developed.

BIBLIOGRAPHY:

Hicks, B.B., and J.D. Womack. 1990. Dry Deposition Inferential Measurement. Test of the Filterpack for Measuring HNO_3. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Atmospheric Turbulence and Diffusion Laboratory, Oak Ridge, TN. In preparation.

U.S. EPA. 1987. National Dry Deposition Network, First Annual Progress Report. U.S. Environmental Protection Agency, Research Triangle Park, NC. July 1987. 52 pp.

H.4 INDICATOR: Ionic Constituents in Precipitation

CATEGORY: Stressor/ Chemical

STATUS: High-Priority Research

APPLICATION: In the atmosphere, chemicals emissions from natural and man-made sources are subjected to physical, chemical, and photochemical processes, which may produce transformation products that can be as toxic as or more toxic to ecological resources than the parent chemicals. The atmosphere serves as the conduit from emissions sources to the biosphere. Once chemicals are emitted into the atmosphere, their pathways to receptors in terrestrial and aquatic ecosystems are a function of a variety of factors. Atmospheric residence times depend upon characteristics such as mode and rate of emission, atmospheric transformations, and physical state.

Chemical deposition in wetfall is monitored by several research projects in the United States and Canada. Chemical deposition, coupled with other pollutants, may have direct and indirect adverse impacts on terrestrial vegetation and aquatic biota. For direct impacts on vegetation, H^+ appears to be the ion of interest. However, for indirect impacts on vegetation, all nutrient cycles are important. Therefore, the nine major ions measured by the wetfall networks appear to be important. Because of the interest in assessing the effects of acidic deposition on vegetation and the possible interaction of acidic deposition with other pollutants, it is important to continue to monitor these nine ions across the United States.

Although much is known about the effects of gaseous pollutants, such as episodic ozone (see indicator H.1) and SO_2 (see indicator H.2) exposures on crops, little is known about ion concentrations that may impact vegetation through nutrient cycling modifications. Although Lefohn and Moser (1989) have discussed episodic exposure concepts, it appears that the calculation of monthly or annual means may suffice at this time. Little research has been performed to assess the importance of concentration, duration, frequency, and time between episodes for the ions on vegetation. The use of long-term integrated values of pollutant loadings may be sufficient to evaluate effects on nutrient cycling mechanisms.

Those assessing the possible effects of acidic deposition on soils and aquatic resources have used deposition values integrated over an annual period to estimate effects. However, the use of an annual deposition rate assumes that episodic and nonepisodic wetfall events have no differential impacts on ecological resources. The use of a deposition exposure parameter for assessing possible effects ignores the temporal variability of wetfall and assumes that ecological resources do not respond differently to similar exposures over different growth periods. When long-term averages are used, it is assumed that the temporal variability associated with biological processes occurring within the soil ecosystem is decoupled from the temporal nature of wetfall. Future research should explore the validity of these assumptions.

INDEX PERIOD: Concentrations of the ions would be measured throughout the year. For existing long-term monitoring networks, these ions are monitored throughout the year in most cases.

MEASUREMENTS: Concentrations of the ions would be measured on an integrated weekly basis. Candidate ions include H^+, Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, SO_4^{2-}, NO_3^-, and Cl^- in rain, snow, fog, and cloud water. The most extensive precipitation chemistry monitoring activity has been associated with the National Atmospheric Deposition Network (NADP)/National Trends Network (NTN). Precipitation samples are collected by the NADP/NTN network on a weekly basis. The wetfall is collected in a large bucket by an apparatus that opens only when precipitation is sensed. Concurrently, a rain gauge measures the amount of precipitation associated with the wetfall event. In addition, the sampling network of the Multistate Atmospheric Power Production Pollution Study/Research in Acidity from Industrial Emissions Program, the SURE sampling network of the Electric Power Research Institute, and the Utility Acid Precipitation Study Program sampling network, although not as geographically extensive, do provide wet deposition data on a daily and/or event basis. The Mountain Cloud Chemistry Program has collected cloud water samples and precipitation samples.

VARIABILITY: The expected spatial variability of ion concentrations within a landscape sampling unit should produce ranges that deviate <20% from the mean value. The expected temporal variability of ion concentrations throughout the year could produce ranges that deviate up to 100% of the mean value.

PRIMARY PROBLEMS: Research results to date apparently have not indicated that acidic deposition exposures at ambient levels result in direct effects on vegetation. Little is known concerning the ion exposure regimes (concentration, frequency, duration, and time between events) that are responsible for eliciting biological responses. Therefore, it is difficult to recommend, for the nine ions measured, specific exposure indices for summarizing the weekly or event wetfall measurements collected.

REFERENCES:

Lefohn, A.S., and T. Moser. 1989. Exposure Indicators for Monitoring Air Quality in the Environment. Prepared for the Environmental Monitoring and Assessment Program (EMAP) of the U.S. Environmental Protection Agency. A.S.L. and Associates, Helena, MT.

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NAPAP. 1987. Interim assessment: The causes and effects of acid deposition. Vol. I: Executive summary. National Acid Precipitation Assessment Program, U.S. Government Printing Office, Washington, DC.

H.5 INDICATOR: Metals and Organics (Toxins)

CATEGORY: Stressor/ Chemical

STATUS: Research

APPLICATION: Airborne toxic chemicals, either individually or in combination, may threaten the productivity, stability, and diversity of terrestrial and aquatic ecosystems. The effects from chronic deposition of airborne toxic chemicals on terrestrial and aquatic organisms and their potential interaction with other stressors (abiotic and biotic) to induce antagonistic to synergistic effects are unknown. The low biodegradability of many toxic compounds allows them to remain ecologically harmful for long periods. The persistence of these compounds can result in adverse biological effects by incorporation and accumulation into food chains and disruption of ecological processes. The degree of ecological impact depends on the deposition rate, toxicity, environmental fate of the pollutant(s), and organism sensitivity.

Toxic chemicals enter the atmosphere from a variety of anthropogenic emission sources, such as chemical, metal, plastic, and pulp/paper industries; oil refineries; combustion of coal and municipal wastes; incinerators; motor vehicles; aircraft; dry cleaning operations; agriculture stubble burning; and agricultural use. Broadly grouped, these chemicals, gaseous and particulate, fall into two categories: (1) organic compounds (which includes volatile organic compounds and pesticides) and (2) trace metals.

In the atmosphere, these and other more benign chemical emissions are subjected to physical, chemical, and photochemical processes, which may produce transformation products that can be as toxic as or more toxic to ecological resources than the parent chemicals. Once chemicals are emitted into the atmosphere, their pathways to receptors in terrestrial and aquatic ecosystems are a function of a variety of factors, including local meteorological conditions and the physical and chemical properties of the compounds themselves. Air toxin concentrations and deposition rates can be measured and compared among all regions of the United States.

INDEX PERIOD: If airborne toxic chemicals are not monitored continuously by the EMAP-Air and Deposition Monitoring Network (Bromberg et al. 1989), a synoptic measure of air toxin concentrations should occur during summer, when vegetation growth and susceptibility to air pollutants is greatest.

MEASUREMENTS: Assuming that the appropriate sampling equipment is incorporated in the EMAP-Air and Deposition Monitoring Network, monitoring costs for both volatile organic carbons and pesticides are estimated as $700 a sample at each site or $350 for either group alone (Bromberg et al. 1989). The additional cost to measure trace metals was not estimated.

If only air toxin emissions data such as the Toxic Release Inventory (Poje et al. 1989) is available, ambient concentrations and deposition estimates for resource sampling units could be estimated from atmospheric models. A reasonable qualitative understanding of atmospheric transport and deposition processes currently exists. Knowledge of chemical transformations, especially of the large number of organic substances, is incomplete. Despite the degree of knowledge that exists for atmospheric processes, it is difficult to quantify the complete atmospheric pathway for a particular substance between source and receptor. However, residence times of chemicals in the atmosphere determine how far a particular substance is likely to move away from its emission source. Therefore, atmospheric residence time is a useful indicator for determining the likely gross depositional distribution of a particular chemical, given known prevalent meteorological conditions. Models for estimating residence times have been generated.

VARIABILITY: The expected spatial and temporal variabilities of airborne toxic chemicals within a landscape sampling unit and during the year, respectively, were not estimated.

PRIMARY PROBLEMS: The environmental exposure of remote areas to airborne organic chemicals and trace metals has not been continuously measured. Methods development or improvement projects are needs for some metals and most organic compounds.

REFERENCES:

Bromberg, S., E. Edgerton, J. Gibson, and D. Holland. 1989. Air/deposition monitoring for the Environmental Monitoring and Assessment Program (EMAP) (draft). U.S. Environmental Protection Agency, Atmospheric Research and Exposure Assessment Laboratory, Research Triangle Park, NC.

Poje, J., N.L. Dean, and J.B. Randall. 1989. Danger downwind: A report on the release of billions of pounds of toxic air pollutants. National Wildlife Federation, Washington, DC.

H.6 INDICATOR: Free Radicals

CATEGORY: Stressor/ Chemical

STATUS: Research

APPLICATION: The lowest few kilometers of the troposphere typically contain the highest concentration of reactive gases emitted by both natural and anthropogenic sources. A complex series of oxidation reactions converts primary emissions to secondary compounds that manifest themselves as components of smog and acidic deposition. The products of these reactions generally have lifetimes of several days. In the photochemical process, unusually high concentrations of free-radicals (e.g., OH, HO_2, NO_2) are generated. These short-lived compounds (lifetime of seconds) are highly energetic and, upon exposure to vegetation, could be disruptive to its normal biochemistry.

INDEX PERIOD: The sampling period would be continuous throughout the year.

MEASUREMENTS: Direct measurements of free radicals are not possible at this time, although kinetic models and surrogate species provide reasonable estimates. Laboratory experiments should first be devised to test this hypothesis.

VARIABILITY: The expected temporal variabilities of free radicals throughout the year would produce ranges that deviate 100% from their mean values. The expected spatial variabilities of free radicals within a landscape sampling unit were not estimated.

PRIMARY PROBLEMS: Serious problems exist in accurate, controlled generation of free radicals and in measurements and estimations of their concentrations.

BIBLIOGRAPHY:

Possanzini, M., A. Febo, and A. Liberti. 1983. New design of a high-performance denuder for the sampling of atmospheric pollutants. Atmos. Environ. 17:2605.

H.7 INDICATOR: Carbon Dioxide

CATEGORY: Stressor/ Chemical

STATUS: Research

APPLICATION: Although not the greatest absorber of infrared radiation per molecule, the huge flux of carbon into the troposphere by fossil fuel sources has made CO_2 a leading factor in long-term climate trends (Schneider 1989). Also, the potential fertilization effect of increased CO_2 concentrations on all vegetation types makes it a potentially important atmospheric stressor indicator.

INDEX PERIOD: This indicator would be monitored throughout the year because of its high variability among seasons.

MEASUREMENTS: The Geophysical Monitoring for Climatic Change Division of the National Oceanic and Atmospheric Administration has been monitoring CO_2 at two Alaskan coastal stations since 1980; a third coastal station in Florida was added in 1984. Monitoring techniques need to be developed for and extended to continental interiors to increase the accuracy of estimating interior distributions of direct CO_2 exposure and important sources and sinks areas in the carbon cycle (Tans et al. 1990).

VARIABILITY: The expected spatial and temporal variabilities of CO_2 concentration within a landscape sampling unit and during the year, respectively, were not estimated.

PRIMARY PROBLEMS: Very sophisticated measurements are needed over large spatial scales.

REFERENCES:

Schneider, S.H. 1989. The greenhouse effect: Science and policy. Science 243:771-781.

Tans, P.P., I.Y. Fung, and T. Takahashi. 1990. Observational constraints on the global atmospheric CO_2 budget. Science 247:1431-1438.

H.8 INDICATOR Other Greenhouse Gases

CATEGORY: Stressor/ Physical

STATUS: Research

APPLICATION: There is evidence that the chemistry of the global troposphere has been changing and will continue to change. The result may be significant changes in climate that could affect the condition of ecological resources. The chemistry of the free troposphere is characterized by gases which absorb infrared radiation yet have little direct effect on vegetation (e.g., CH_4, N_2O, O_3 hydrocarbons, and halocarbons), and their increase has led to the greenhouse theory of global warming (Schneider 1989).

INDEX PERIOD: The tropospheric gases would be monitored throughout the year because of their high variabilities among seasons.

MEASUREMENTS: Measurements of the free troposphere for greenhouse gases are needed at several latitudes, integrating over various time intervals; their concentrations would be reported as annual and seasonal averages.

VARIABILITY: The expected spatial variability and temporal variability of tropospheric chemistry within a landscape sampling unit and during the year, respectively, were not estimated.

PRIMARY PROBLEMS: Very sophisticated measurements are needed over large spatial scales.

REFERENCES:

Schneider, S.H. 1989. The greenhouse effect: Science and policy. Science 243:771-781.

H.9 INDICATOR: Ultraviolet Type B Radiation

CATEGORY: Stressor/ Physical

STATUS: Research

APPLICATION: Molina and Rowland (1974) hypothesized that photochemical reactions involving halocarbons could diminish the protective ozone layer in the stratosphere. There is now evidence which validates this hypothesis (Cicerone 1987; McElroy and Salawitch 1989). An important consequence of this stratospheric change is increased ultraviolet type-B radiation (UV-B) exposure in the lower atmosphere and at the earth's surface. Increased UV-B intensity to terrestrial organisms may have a significant effect on reproduction. Increased intensity may also stress aquatic microorganisms, which in turn would affect organisms of higher trophic levels.

INDEX PERIOD: Strong diurnal and seasonal variability would require near-continuous monitoring during daylight hours.

MEASUREMENTS: Continuous measurements of incident UV-B radiation are needed at several latitudes. Such measurements are made at several U.S. laboratories, and historical data should be readily available. These spectroradiometric measurements are sophisticated and of high precision.

VARIABILITY: Strong diurnal and seasonal variability is anticipated. The expected spatial and temporal variabilities of UV-B radiation within a landscape sampling unit and during the year, respectively, were not estimated.

PRIMARY PROBLEMS: Calibration standards for the UV-B monitors are also needed. The sensitivity of ecological resources to ultraviolet radiation is largely unknown.

REFERENCES:

Molina, M.J., and F.S. Rowland. 1974. Stratospheric sink for chlorofluoromethanes: Chlorine atom-catalyzed destruction of ozone. Nature 249:810-812.

Cicerone, R.J. 1987. Changes in stratospheric ozone. Science 237:35-42.

McElroy, M.B., and R.J. Salawitch. 1989. Changing composition of the global stratosphere. Science 243:763-770.

H.10 INDICATOR: Airborne Particles

CATEGORY: Stressor/ Physical

STATUS: Research

APPLICATION: Extremes of particle loading in the atmosphere could have short-term effects on ecological resources. Such extremes include severe dust storms, volcanic activity, and fumigation of emissions from electricity-generating plants. In addition to possible health effects, particle loading is principally related to atmospheric extinction and the assessment endpoint of visibility. Particle loading could be particularly acute in arid regions where visibility is generally outstanding.

INDEX PERIOD: The sampling period would be continuous over all seasons.

MEASUREMENTS: Particle loading is readily measured by sampling air through filters and processing filters by gravimetric analysis. Visibility measurements are much more sophisticated and subjective.

VARIABILITY: Diurnal and seasonal variability in particle loading is significant. Visibility is highly variable and depends strongly on sunlight and sun angle conditions.

PRIMARY PROBLEMS: Visibility measurements are problematic, as indicated above.

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